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Soil quality in the Canadian context – 1988 discussion papers

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Land Resource Research Centre
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Cover illustration
The dots on the map represent Agriculture Canada research establishments.

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PREFACE

Urgency to monitor systematically the trends in soil quality in Canada has manifested itself only in the last three years. Before this there had been a long history of vague concern for the health of agricultural land, but to a large extent it seemed easily corrected by applications of fertilizer. The extensive discussions among experts all across the country that took place in the attempts to set up a National Soil Conservation Program came back repeatedly to the need for monitoring soil quality trends. Before embarking upon a major monitoring program, it is absolutely essential to understand what is meant by soil quality, and the extent to which we are talking of a number of soil qualities. It is also important to select the key components which can be practically addressed with the resources available and which are central to the preservation of the agricultural land base.

The links to concepts of sustainable development are fairly obvious and I would anticipate that the papers would help to provide a sound foundation on which to build programs that future generations will regard as historically responsible.

This monograph covers the criteria that need to be used for evaluating soil quality including differences in emphasis from east to west of the country. It covers both mineral and organic soils, both extremely sensitive to mistreatment in their own ways. A proposed classification scheme is presented as a rather important component for ordering our knowledge. The special role of organic matter in soils is discussed from basic principles and description of basic components through to the various effects on the practical attributes of soils use for agriculture.

It is fully recognized that the monograph of such limited size could not possibly address all aspects of soil quality and their ramifications. One aspect of soil quality which is not fully addressed in large part because of lack of information, is the quality of soil related to its physical attributes. The role of soil structure in maintaining optimum air and water regimes; the influence of land management on groundwater quality; and many issues related to soil compaction are examples of soil physical quality attributes requiring research attention. Nevertheless, I would commend this report to those seeking a summary of many of the more important aspects of soil quality which can be seriously affected by land management and which have a powerful bearing on the security of our future food supplies.

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CONCEPTS AND CRITERIA OF SOIL QUALITY IN THE CONTEXT OF WESTERN CANADA

DON. F. ACTON

CONCEPTS OF SOIL QUALITY

Everyone seems to have a vision of what is soil quality but rarely a concise and precise definition of it. Anderson (1983) adapted a definition by Leopold (1949) as follows: "Soil quality is the sustained capability of a soil to accept, store and recycle water, nutrients and energy". He considers a quality soil to have: (i) adequate depth for water storage and rooting; (ii) organo-mineral colloids sufficient for retaining moisture and nutrients in various plant-available forms; (iii) no unsuitable chemical conditions such as acidity or salinity; and (iv) a physical condition which promotes the infiltration of moisture and its storage, aeration and the unhindered development of roots. The soil must be capable of handling energy. It should accept, store and recycle the energy contained in organic matter which drives biological processes in the soil, and be able to absorb the dynamic energy of rain drops or wind-borne soil particles which might otherwise dislodge the soil.

Anderson (1983) regards organic matter to be one of the key components of soil quality. We are all aware of how it can be easily lost through soil erosion and is profoundly affected by soil management.

Soil quality and soil productivity are closely interrelated, often in such a way that changes in one can ultimately alter the other. Anderson and Gregorich (1983) identified four ways in which erosion reduces productvity (and, hence, soil quality): (i) loss of soil's capacity to storing plant-available water; (ii) loss of plant nutrients, (iii) degradation of soil structure and (iv) increasing the heterogeneity of soil within a field.

Others such as Pierre et al. (1982) attempted to quantify soil productivity so as to assess long-term loss in productivity due to erosion. They assumed that soil is a major determinant of crop yield because of the environment it provides for root growth (other factors being climate, management and plant genetic potential). Following Neill (1982), Pierre et al. considered five soil parameters - available water capacity, bulk density, aeration, pH and electrical conductivity as the parameters most important to root growth. In addition, he used a weighting factor to accommodate the effects of thickness of the soil layers. Neill (1982) assumed nutrients do not limit plant growth.

Meyer et al. (1985) prepared a long list of standardized measurements for quantifying (quantitating) factors that affect productivity. The soil environment properties include: (a) physical properties - water retention, bulk density, particle size distribution, strength, aggregate stability, infiltration capacity and shrink-swell potentital, (b) chemical

properties - organic carbon, total nitrogen, C:N ratio, nitrate and ammonium, total inorganic and organic phosphorus, CEC, base saturation, pH, and perhaps aluminum saturation, sulfur, micronutrients, soluble salts and sodium absorption ratio (SAR), (c) biological properties - heterotrophic index, soil respiration and (d) soil landscape characteristics slope steepness and length, aspect. They also list ambient environment, plant growth measurements and management details that should be considered in planning erosion productivity experiments.

Renard and Follett (1985) identified soil properties utilized in the Erosion Productivity Impact Calculator (EPIC) model and provided some guidance in erosion or productivity experimentation.

An anonymous and undated report, "Soil Quality Criteria for Agriculture", prepared by a subcommittee of the Alberta Soils Advisory Committee, and printed by Agriculture Canada, identified a number of criteria for assessing the quality of soil for agricultural production. In general, these criteria were represented by soil properties that can be measured quantitatively. The interpretation of the results would require subjective judgement that must consider other factors, such as climatic variables, economic factors, crop species, and management practices. The chemical criteria were as follows: (i) soil reaction, (ii) salt content, (iii) SAR, (iv) potassium concentration, (v) soluble and exchangeable nitrate, (vi) sulfate and chloride, (vii) metals, (viii) organic matter, (ix) foreign carbonaceous materials, and (x) pesticides. The physical criteria included: (i) susceptibility to erosion, (ii) permeability for irrigation, (iii) bulk density, (iv) moisture saturation percentage, (v) moisture supplying capacity, (vi) depth of rooting zone and (vii) stoniness. Finally, they recognized the importance of microbiological criteria but felt there were no simple quantitative means for expressing microbiological processes.

The Soil Quality Working Group of the Alberta Soils Advisory Committee examined the question of soil quality criteria relative to land disturbance and reclamation. Ratings for top soils in the Prairies were based on: (i) reaction, (ii) salinity, (iii) sodicity, (iv) saturation percentage, (v) stoniness, (vi) texture, (vii) moist consistency, (viii) organic carbon and (ix) $CaCO_3$ equivalent. They included gypsum and deleted organic matter content in rating subsoils.

There are a number of excellent review papers on the effects of tillage in American Society of Agronomy sp. Publ. 44 (1982); on the hydraulic properties of soils by Klute; on soil bulk density and mechanical impediment by Cassel; on soil temperature and thermal conductivity by Wierenga et al.; on soil aeration by Erickson. They all allude to the difficulty in making these measurements as well as to the fact that any changes in them, albeit theoretically possible, are not well documented.

CRITERIA OF SOIL QUALITY

The preceding provides a brief overview of some of the key parameters that can be used to measure soil quality. It covers chosen examples, not all. The final selection of criteria will likely depend on more precise definition of objectives. For example, the criteria required to meet a long-term monitoring objective may not necessarily be the same as those required to assess current status of soil quality or to predict

productivity change or erosion loss (i.e. one may wish to include aggregate size and stability to predict erosion loss but it may not be required for monitoring long-term quality change).

Another consideration is that of a reference standard. In Canada, where plough agriculture is barely 100 years old, it is common to use the virgin or cultivated condition as the standard. This may be appropriate for some properties but is is unrealistic for all. Perhaps something less than 10 or 20 years cultivated is a more appropriate standard.

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SOIL QUALITY CRITERIA IN THE CONTEXT OF EASTERN CANADA

D.R.COOTE

INTRODUCTION

This review is concerned with the effects of erosion (both wind and water), acidification and soil compaction on soil quality. "Soil quality" can be viewed in two distinct ways:

A: The concept of a set of criteria for soil quality can imply that predetermined standards will be established in order to decide if a soil can be used for a particular purpose. For example, if the objective of applying soil quality criteria is to maximize agricultural or silvicultural productivity on a unit area of land, then the criteria should reflect the soil's productivity potential for particular crops. This is similar in many ways to the capability classification of soils for agriculture or forestry.

B: Soil quality can also be viewed as simply a statement of the properties of a soil (in which case it would be more correct to use the term "soil qualities").

The concept of soil quality which is used in this paper follows most closely the first of these two definitions.

The deterioration of soil quality as a result of water erosion has been documented in eastern Canada over several decades. Examples are the loss of productivity resulting from erosion in southwestern Ontario (Battison et al. 1984), eastern Ontario (Ripley et al. 1966), Quebec (Dubé 1975), and Prince Edward Island (Stewart and Himelman 1975). However, the only direct monitoring of soil erosion and its effects on soil productivity that is currently taking place is in the potato growing area of northwest New Brunswick (T. L. Chow, pers. comm.). Research using rainfall simulators to study the effects of different soil management practices on soil erosion by rainfall and snow-melt is being done at locations in Ontario, Quebec, and Prince Edward Island (G. J. Wall, G. Meyhus, A. Pesant and J. R. Burney, pers. comms.). The primary purpose of this research is to improve our ability to predict water erosion, and to assess the effect of different soil management options on erosion rates.

Wind erosion is less well documented in eastern Canada, although in recent years there have been incidents of more severe wind erosion in southwestern Ontario (Fitzsimons and Nickling 1982),and parts of the lower St.Lawrence valley in Quebec (F. Fournier, pers. comm.). The problem also occasionally occurs in P.E.I., the Annapolis valley of Nova Scotia and in Newfoundland. Productivity loss has not been well documented, although it is suspected that damage to plants from abrasion by drifting sand has caused some yield loss.

Soil acidification is well understood, though not well documented because it is often difficult to distinguish between soils of naturally low pH and those that have become acidified as a result of fertilizer use and acid rain. For example, soil test laboratory results from P.E.I. (Veinot

1978) demonstrated a steady decline in pH of samples submitted over a number of years. Reports of yield loss in the sandy soils of southern Ontario (Protz et al. 1977) cite areas of pH below 4.0 as a contributing factor. The soils involved in this case would normally be considered calcareous, which they still were below the plow layer. A large percentage of the soils of the Canadian Shield, eastern Quebec and much of the Atlantic region are podzolic, so low pH is an expected and natural phenomenon. Liming in these areas is a normal practice for crop production and correcting any accelerated accidification is a minor inconvenience with relatively low cost. However, newly acidifying areas such as those in southern Ontario may present farmers with a new set of constraints and needs.

Soil compaction is the least well understood or documented problem, but possiblly the one with the greatest potential for yield loss. Soil compaction manifests itself either as a very poorly structured Ap horizon or as a dense, slowly permeable layer immediatly below the Ap (a "plow-pan"). The former may be partly the result of the type of crop that is being grown (eg continuous corn is often associated with this type of "compaction"). The sub-surface compacted layer may be more the result of tillage, high wheel loads and working the soil in wet conditions.

There are few measured data within farmers' fields that can be used to substantiate the extent or even the presence of soil compaction. For example, at one site in eastern Ontario at which the farmer claimed to have a "compaction" problem, examination of the soil structure and measurement of Ksat indicated good conditions for root development (J. A. McKeague, C. Wang, pers. comm.) The field had been out of continuous corn for one year, and was in barley at the time it was investigated. It is not known if the one year of barley had corrected the problem, or if there had not been one in the first place. Farmers in southwestern Ontario have reported that subsurface drains at 50 ft spacings are no longer functioning adequately, and so new tile drains are being installed between the existing drains. Some of this re-installation of drains may also have resulted from pressure by drainage companies. In the St.Lawrence lowlands of Quebec soil compaction is widely reported under crops like corn and sugarbeet (G. Meyhus, pers. comm). Some farmers have been using sub-soilers, at considerable expense, in an effort to improve the movement of water through the worst affected soils.

In the potato growing area of New Brunswick soil compaction seems to be partly associated with erosion. The loss of surface layers over naturally compact subsoils results in a more dense Ap, and may account for some of the "compaction" problems reported. The heavy, vibrating harvesting equipment working in wet soils might also be expected to lead to some soil compaction.

Research plots in clay soils of southwestern Quebec have demonstrated the role of tire pressure, wheel slip and soil wetness in increasing soil bulk density during field operations (Raghavan et al. 1977a,b). Corn roots have been shown to aggravate soil structure problems (Reid and Goss 1982). This seems to have been corroborated by laboratory research with a southern Ontario soil (B. Kay, pers. comm.). It was also found that the roots of certain other plants, such as brome grass, caused strengthening of soil structure. These effects appear to vary greatly seasonally, as

demonstrated in field and laboratory plots in Quebec, using a water-stable aggregation index (D. Angers, pers. comm.). Some current research is aimed at defining soil "compaction" in a way that might be more quantitatively applied in the field (Kay et al. 1986). Morphological interpretations of biopores and root distribution and soil structure have been shown to lead to reasonably reliable prediction of soil hydraulic conductivity class (Wang et al. 1985b).

The challenge, then, is to identify, define and quantify those soil properties that are affected by erosion, compaction and acidification, and to be able to specify limits for each (singly or in combination with others) so that soil productivity can be characterized. At the same time, these limits should be sufficiently sensitive that changes in soil productivity as a result of soil degradation can be detected, allowing the establishment of an "early warning system" for soil productivity loss.

CRITERIA

For the purpose of this discussion, soil quality criteria can best be divided into two types: i. those for determining the extent and severity of a problem that has already occurred (accumulated effect); and ii. those that diagnose a potential problem (risk).

Soil Erosion

i. Accumulated erosion effects: Criteria for determining soil productivity or quality loss resulting from erosion are not well established. Depth of topsoil is commonly used as an indicator, but this is a very poor criterion. Mixing that occurs as the A horizon is diminished results in a continuous change, so that the concept of "depth" of topsoil lost is almost meaningless. Changes to rooting depth and/or water holding capacity are only slightly better. There is seldom a distinct boundary below which roots will not penetrate, or through which water will not move vertically, so there is not a direct relationship between these measurements and soil erosion. It is also possibile for a subsoil to have greater water holding capacity than the surface soil. Soil productivity loss has been reported in terms of yield loss per unit depth of soil eroded (Lyles 1975). This does not take account of the non-linearity and mixing problem, or soil management variability, and lacks a scientific basis. Where there are distinct subsoil layers that can be identified readily (eg peak Fe concentrations - Olson and Beavers 1987) then depth change may provide a criterion of soil loss, but not necessarily of productivity loss. A change in the relative abundance of 137Cs in the soil provides another measure of soil loss, but is limited to erosion that occured in the last 20 years (deJong et al. 1983). In view of the uncertainty of erosion prior to the last 2 decades, this may be the best criterion we have at present. It also provides a check on in-field deposion of eroded soil, which may account for some of the variability seen in soil depth measurements.

   Changes in soil physical properties resulting from erosion are not well documented. In some cases there seems to be an increase in sand

content, with a corresponding loss of clay and organic matter associated with it as a result of greater erodibility and transport potential of these materials (Spires and Miller 1978). On the other hand, sand is often the dominant fraction deposited in zones of deposition within the field further down the slope (Bourget and Mclean 1963), and increases in sand content can therefore be caused by either erosion or deposition, and this can be misleading. Texture (and structure) change may also result from mixing of surface with subsurface layers of different texture and this would be difficult to distinguish from the effect of differential erosion at the surface.

ii. Erosion risk: The most frequently used method of estimating the risk of soil erosion by rainfall is the Universal Soil Loss Equation (USLE). The USLE factors have been established over many years in the U.S. The minimum requirement is to know soil texture and organic matter content, slope, length of slope, and rainfall energy (Wischmeier and Smith 1978). Under Canadian conditions the climatic factor is evidently far more complex. The effect of freezing and thawing on soil erodibility is still not entirely clear, although it is estimated that freshly thawed surface soil that has frozen soil beneath it is probably 10-15 times more erodible than the "mean annual" estimate that comes from the USLE nomograph (Coote et al. 1988a; Wall et al. 1988). On the other hand, in late summer when the soil surface is hard and dry, and when frozen solid in winter, erodibility may be lower than the USLE estimate (Kirby and Meyhus 1987). The determination of seasonal erodibility is critical for estimating water erosion risk for different crop and soil management scenarios in Canada.

The application of climate factors for water erosion in Canada must take into account snow melt runoff and frequency of freeze-thaw cycles. The former has been very superficially approached by the USLE documentation using total winter precipitation (Wischmeier and Smith 1978), but nothing has yet been done to include of the latter.

The US Wind Erosion Equation is the only current procedure for estimating wind erosion risk in eastern Canada (Woodruff and Siddoway 1965). An alternative method that has been successfully applied in the Prairie region (Coote et al. 1988b) needs soil moisture data that are not yet available in Eastern Canada. As with water erosion, wind erodibility appears to be greatest immediately following spring thaw when structure at the surface is in a fine, granular state of aggregation in dry soils (Hilliard et al, 1988). Tables of texture related erodibility from the US appear to underestimate the wind erodibility of Canadian soils in the early spring when the problem is usually most severe.

Soil Acidification

i. Accumulated acidity: The determination of the degree of soil acidification that has occurred at a site is, for practical reasons, essentially limited to that arising from fertilizers. It can only be done with any reliability if a similar site in the same zone that has received no fertilizer or lime is available for comparison. Variation

of pH between fields of the same soil type in the same region, with different fertilizer and liming histories, can provide a preliminary estimate of past acidification. Criteria are soil pH, base exchange capacity and base saturation. One or more of these parameters has been determined by provincial soil testing laboratories on farmers' soil samples for decades. Recommendations are usually given in terms of lime needed to restore the pH of the soil to a predetermined level judged suitable for a particular crop being grown on that soil type. Where soil test results are available for the same field over a period of years, an estimate of acidification rate can be obtained. Care must be taken in comparing pH values obtained in this way if the field was sampled at different times of year, or if the laboratory methods have changed.

ii. Acidification risk: The risk of soil acidification can be estimated from data on exchangeable bases and the "buffering capacity". If necessary, exchangeable bases can be estimated from pH and cation exchange capacity (CEC), and CEC can be estimated from texture and organic matter content (Wang and Coote 1980).

Acidification due to fertilizers can be estimated from known fertilizer use. Tables of acidity generated by inputs of different fertilizers have been published (Tisdale and Nelson 1985). Acid rain input to the soil is also generally known and has been published in the form of a pattern over eastern Canada linking point values determined from atmospheric deposition data collected at sampling sites (Barrie et al. 1980). A model to estimate soil acidification rate has been developed by the author that considers base and acid cycling in the soil and crop, and for which both fertilizer and acid rain can serve as input to a particular soil type under a predetermined cropping practice.

Soil Compaction

i. Accumulated compaction: Soil compaction that has already occurred has been estimated from a number of soil physical properties. These include bulk density, Ksat, penetrometer resistance, oxygen diffusion rates, porosity, structure, micro-morphology, and root distribution patterns (Coote and Ramsey 1983; Taylor et al. 1981; Wang et al. 1985a). For each of these there appears to be a set of problems associated with site to site variability, texture and moisture content.

Bulk density (BD) is one of the most appealing measurements for assessing soil compaction. It is a direct measurement of a soil property that is, conceptually, a clear indicator of the tightness of packing of soil particles (ie. "soil compaction"). On closer examination, however, some difficulties appear. Firstly, BD is a function of soil particle density for any given "degree of compaction". Particle density decreases from sand to clay to organic matter. Among clays, density varies with mineralogy. Secondly, soils high in clay or organic matter content shrink or swell with changes in moisture content, thus changing bulk density irrespective of compaction.

Third, bulk density is difficult and time consuming to measure accurately in the field. Some degree of compression or shattering, depending on moisture content, is almost inevitable with coring methods (Blake 1965). Attenuation of radiation from a source lowered into a hole in the soil is less destructive and much more rapid. Recent developments with parallel two-probe instruments have simplified the measurement of depth variation of BD (Gameda et al. 1983). However, it is only possible to measure wet density by this method, so accurate soil moisture measurements are needed to derive dry bulk density.

Research in the Ottawa area suggests that in situ Ksat is one of the prefered indicators of "compaction" (Coote and Ramsey 1983). This parameter has been determined using the air-entry permeameter, which is time-consuming. Variability in Ksat is very high when measured in the field. Use of the Guelph permeameter might increase the number of determinations that can be made, and thus may provide better estimates of mean Ksat at each soil depth zone in those soils in which the method works well. The simple morphological method using soil structure (including pores) has been successful in estimating both vertical (McKeague et al. 1986) and horizontal Ksat (Wang et al. 1985b).

Penetrometer resistance (PR) is also conceptually appealing because it evokes the idea of roots attempting to penetrate into the subsoil. However, PR is highly dependent on soil moisture, and thus must either be used in conjunction with a moisture:PR calibration curve, or it must be limited to comparisons within a single site where soil moisture is unlikely to vary more than a few percent. Instruments with automatic data loggers provide very rapid results, but interpretation and establishment of limits remains difficult.

Oxygen diffusion rates (ODR) provide another means of indirect measurement of soil compaction (Lemon and Erickson 1952). Oxygen movement to an electrode that can be set at any depth in the soil simulates the oxygen supply to plant roots, thus indicating the relative quality of the gaseous environment of the root - low values represent compact conditions in fine textured soils. The method tends to produce results that have very high variability even in the same site (Coote and Ramsey 1983). The soil immediately surrounding the very small (4mm) electrode determines the ODR, so that whether the electrode is in an aggregate or in an inter-ped macropore will greatly influence the value obtained.

Porosity is a term with numerous connotations. It can be used to describe the total pore space at any moisture content from saturation to oven-dry, or the air-filled pore space at a specified moisture content or tension (Vomocil 1965). It is a direct measurement of soil compaction closely related to bulk density. It also suffers from the same difficulties as BD.

Structure (macro-morphology) is one of the best methods of identifying a compacted soil (McKeague et al. 1987). Descriptions of the size, shape and strength of peds convey much information about the condition of the soil. However, they can be subjective and the investigator

should follow closely the quantitatively defined method (McKeague et al. 1986) in describing soil morphology.

Soil micro-morphology provides more detailed information on particle packing, orientation and bonding. It is hard to quantify, but may add substantially to other observations, measured data on BD, etc.

Root densities and distribution patterns can be direct indicators of soil compaction problems. However, quantification is destructive and tedious (Stone et al. 1987). Root distribution patterns can identify compacted horizons and discontinuities in them. Used in conjunction with other data, they may provide the clearest information concerning the nature and extent of the soil compaction problem.

ii. Compaction risk: Soil compaction risk has only been estimated to date using a crude relationship between texture, drainage and machinery traffic (Fox and Coote, 1986). This relationship arose from unquantified observations, and is therefore only a dimensionless index. Compactability, developed from standard Proctor density tests, provides a laboratory index suitable for engineering interpretations, and it has been used for soil susceptability to compaction in transmission corridor rights of way (McBride 1983). However, soil ratings obtained this way do not seem to reflect experience with agricultural "compaction" problems. No other risk assessment methodology has yet been published, though Guelph researchers are currently working on one (R. McBride, pers. comm.).

DISCUSSION AND CONCLUSIONS

The list of possible criteria for assessing mineral soil quality is long. Scientific data needed for objective selection of criteria and testing of models is generally lacking. Researchers often prefer those chemical and physical properties which they know how to interpret from experience. Reaching a consensus on these criteria that should be recommended for a soil quality assessment and monitoring project may not yet be possible.

It is inevitable that financial constraints will seriously affect the scope of any soil quality assessment project. It is therefore essential that the greatest amount of information (rather than "data") be obtained as inexpensively as possible. With this in mind, certain observations that provide more information about a soil's quality than others should be selected first.

i) Depth to the parent material or to a root-restricting layer (whichever is reached first), texture, colour, structure, root and biopore distribution, slope, and drainage class can all be measured or estimated at a site without the use of sophisticated instruments or analyses. Interpretive ratings based on these observations, such as hydraulic conductivity class (McKeague et al. 1986), provide a further step in maximizing the use of this relatively easily obtained information. Visual evidence of wind or water erosion should also be noted and described. The landform, land use and farming system should be recorded at every site.

ii) The next stage in a soil quality site investigation should probably involve the simpler laboratory determinations that provide information related to soil productivity. Surface layer organic matter content, C/N ratio, pH, CEC and exchangeable bases, when considered together with the observations already gathered in the field, provide an insight into soil fertility, and soil sensitivity to acidification. Organic matter content adds an indication of soil erodibility and susceptibility to compaction, especially when differences are seen between sites in similar soils or if changes are noted over time. Except for pH, which is rather subject to seasonal variation, these laboratory measurements are fairly sensitive to changes brought about by erosion or intensive cultivation.

iii) The next stage of soil quality assessment will require a complete particle size analysis by depth intervals related to the profile characteristics, to quantify the estimations made in the field by hand texturing. This may be followed by a set of soil moisture desorption curves (at similar depth intervals) from which available moisture holding capacity, pore size distribution and air-filled pores (at a particular soil water potential) can be determined. This information is useful in characterizing the degree and nature of any compaction that may be occuring. Extractable P and K should should also be determined to further aid in assessing soil fertility.

iv) Finally, the investigation can follow the interests of the investigator to the extent that time and budget allow. Many of the determinations discussed in earlier sections could be undertaken if the purpose is clear and the interpretation is understood.

The first three stages of soil quality investigation mentioned above represent the minimum that should be undertaken for mineral soil monitoring in eastern Canada at each of the three following levels of interest respectively:

i) Generalized mapping of risk and presence of soil erosion and compaction problems at a wide range of scales.
ii) Establishment of a network of simple "bench-mark" sites that could be returned to at intervals of 5 to 10 years to evaluate changes that may be significant to regional level soil productivity, and for comparison of soil quality for agriculture between soil map units or sites mapped at scales of 1:50,000 or larger.
iii) Establishment of detailed soil quality monitoring sites in soils that are regionally or locally important, or soils for which degradation monitoring is of high priority because of environmental or economic reasons.

The ultimate level of soil quality investigation (iv) should probably be reserved for sites at which research projects are being undertaken, and for which responsibility for interpretation and presentation of data rests primarily with the researcher involved.

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QUALITY CRITERIA FOR ORGANIC SOILS

M. LÉVESQUE and S.P. MATHUR

INTRODUCTION

Not so long ago, Canadian peatlands were regarded as wastelands which hindered the development of nearby mineral soils, and transport. To-day, the organic soils of several regions are highly valued as they produce crops worth 75 millions of dollars (1988) in Canada. Obviously, this change in attitude towards peatlands occured due to the development of new techniques in soil management, and the establishment of a viable horticultural industry.

Peatlands occur widely in temperate and subarctic zones which had been glaciated, while in warmer climates they tend to be restricted to high elevations, riverine floodplains, deltas and estuaries. Consequently, about 12% of the land area in Canada is covered by at least 40 cm of moderately decomposed or 60 cm of less decomposed organic materials. Organic soils are the dominant soils in Canada on 927,113 km^2 and occur in association with other soils on an additional 152,751 km^2. Approximately 60% of these soils are permanently frozen (Clayton *et al*. 1977, Tarnocai 1980). Peatlands areas in agricultural use are situated in the more temperate regions of the country; therefore, the cultivated peatlands are of limited extent, and not in proportion to the total peatland areas. For instance, Manitoba which has over 20 million hectares of peatlands has very little of it under cultivation. Conversely, southern Ontario where peatlands is scarce compared to the immense tracts of it in the north, has Canada's second largest concentration of organic soils under cultivation (6500 ha). The situation is similar in Quebec where 7,100 ha under cultivation are nearly all concentrated in the south-western region. Proportionally speaking, however, there is a greater use of peatlands in British Columbia, with its 1250 ha under cultivation. B.C. is something of a special case in that, in addition to the Lower Fraser organic deposits which are mainly used for vegetables, there are the meadow fens of the Interior Plateau devoted to feed crops and pasture lands.

Thus, five important areas of cultivated organic soils in Canada are: south-western Quebec, southern Ontario, south-eastern Manitoba, the Lower Fraser valley and the Interior Plateau of B.C. This pattern of distribution took shape under the influence of factors such as climate, market proximity, and the quality and nature of the organic deposits. Also, cultivated peatlands occupy usually areas contiguous to the best mineral soils in those areas. This means that organic soils must have a high and very specific agricultural potential to have attracted the attention of vegetable producers who invested the necessary resources for the reclamation and cultivation of these soils. So, it will be proper, here, to mention the reasons for which organic soils attract agriculture, in spite of the difficulties of drainage and management of these soils.

Organic soils owe their quality as good plant growth media to a thick mass of partially decomposed organic materials which provides them with the following assets: a high capacity to store water and nutrients - a low

bulk density - a high resistance to extreme physical, chemical and environmental changes - a large pool of N. By nature, organic soils can retain and supply water in larger amounts than mineral soils. Being organic, they pose little resistance to growth of roots. Therefore, under normal conditions, organic soils are the best substrate for crops requiring unimpeded growth of roots, continuous supply of water and nitrogen, without adhering soil particles on the produce. However, not all organic soils have the above desirable attributes throughout their usage. At the same time, unlike mineral soils, cultivated organic soils, inherently, are a nonrenewable resource as drainage, liming, fertilization and tillage spur biochemical oxidation to cause subsidence and ultimately disappearance of the soils (Mathur 1987). During agricultural use, organic soils suffer losses in their manageability and sustainable productivity as organic sublayers are exhumed and exhausted. It is of paramount importance for the proper use and management of organic soils to know the nature, properties and behaviour of organic soils well. Therefore, it is especially important to establish good soil quality criteria to measure changes due to cultivation, and evaluate their impact on their agronomic value. At the same time, this would help in developing means of sustaining their productivity while minimizing organic matter losses and pollution problems.

ORGANIC SOILS AND THEIR PROPERTIES

According to the Canadian taxonomic classification system (CSSC 1978), soils with surficial organic layers of >40 cm in thickness and containing >17% C are said to be organic. By itself, this definition does not allow interpretation with respect to quality and desirable attributes of organic soils. In the agricultural context, an ideal organic soil should have an harmonious combination of intrinsic and acquired properties which contribute to ensure a high level of productivity and crop quality without difficult or costly adjustments.

By nature, organic soils consist of partially degraded plant debris with a low content of mineral matter. In their virgin state, they contain up to 90% water by weight. Hence, the intrinsic properties of newly reclaimed organic soils would be the following ones:

- high organic matter content (>90%)
- high porosity
- low nutrient level
- acidic (pH 3-5)
- high exchange capacity (>100 me/100 g)
- low bulk density (0.05 - 0.20)
- high water holding capacity (300 to 1500% of dry weight)
- low bearing capacity
- biodegradable and thus prone to subsidence

Comparisons of these properties with those of mineral soils bring out characteristic differences, and force many to admit that organic soils hold their agronomic value mainly because of their physical properties (Njos 1978).

Based on a literature survey of general topics related to the nature, properties and utilization of organic soils (Farnham and Finney 1965,

Jasmin et al. 1981, Lévesque 1982, Lévesque et al. 1977, Lévesque and Mathur 1979, Lévesque et al. 1980, Lucas 1982, Mathur and Farnham 1985, Njos 1978, Robinson and Lamb 1975, Schothorst 1982, Valmari 1982), here are listed what could be the desirable attributes of an ideal organic soil, provided adequate fertilization is practised:

1. a mixed botanical composition consisting of sedge, sphagnum moss and wood in the following respective proportion: 60-40-10
2. moderately decomposed (25-35% rubbed fibers or H4-H5)
3. an organic overlay >80 cm
4. slightly acidic (pH 5-6)
5. cation exchange capacity >100 me/100 g
6. a significant proportion of coarse (wood) materials
7. 50-80 cm layer free of water logging, i.e. an aerated surface layer - for the growing season
8. uniform density and porosity in the aerated zone
9. preferably on a sandy substratum
10. some resistance to biodegradation (slow rate of decomposition), partly through presence of adequate amounts of Cu in the soil
11. mineral content of 10-20%
12. sufficient bearing capacity (>5 $kg.cm^{-2}$)
13. adequate hydraulic conductivity (Ksat.>1.0 $m.d^{-1}$)

Several of these attributes were barely or not sufficiently assessed in relation to organic soil quality; similarly their significance or contribution to soil productivity is far from being established and understood. In subsequent sections, these considerations will receive further attention.

If it is important to recognize the organic soils assets, it is equally important to know the main constraints of these soils. These constraints could be grouped as follows:

1. acidic in nature
2. biodegradable - prone to subsidence
3. special reclamation and management practices required
4. low bearing capacity
5. slow warming up, and thus usually cooler than adjacent mineral soils during the seed germination period
6. water storage generally favoured over water transmission
7. densification and compaction with time
8. crop choice relatively limited

Again, these features will be discussed in the context of long-term utilization of organic soils in subsequent sections.

GENERAL CHANGES ASSOCIATED WITH THE RECLAMATION AND CULTIVATION OF ORGANIC SOILS

As soon as a peatland is drained, the natural processes of peat formation are stopped, and the degradation forces already at work intensify their action. So, as a result of drainage implementation, coupled with liming, fertilization and tillage, the peat which constitutes the parent materials for organic soils evolves and changes. Some of the changes may be regarded as beneficial such as reduction of acidity, release of N upon

decomposition, and physical breakdown of coarse plant fragments. However, the changes due to cultivation are rather negative and contribute to the deterioration of organic soils through the humification and mineralization of the organic parent materials. These two processes are mainly responsible for the densification, compaction, lowering of total porosity, low rate of water infiltration, translocation of nutrients and fine particles down in the soil profile, and others, subsidence being not the least. These changes are important and deserve further examination. This will be done by reviewing some pertinent work carried out in this country as well as abroad in relation to several of these topics.

PROBLEMS IN USING ORGANIC SOILS AS PERCEIVED BY PRODUCERS

Here are listed the main organic soil degradation problems as they are perceived by the producers, and realized by our own observations in southern Ontario, south western Quebec and southern Brithish Columbia.

1. Ponding of water due to concentration of fine particles or clay at the soil surface.
2. Low rate of water infiltration during periods of intense precipitations. This causes damages to crops and restricts field operations.
3. Compaction of the surface layer mainly caused by overhead irrigation used to keep the soil in place following seeding.
4. Damage caused to young plants, particularly leafy salad crops on organic soils of >20% mineral content, by blowing sand or silt particles during dry periods in spring.
5. Increasing islands of mineral soils with the progressive disappearance of the organic overlay. This may result in losses of cultivated areas because of resurgence of unsuitable mineral substratum. The losses could be as high as 1% per year; several producers reported losses of 20% of their usable and productive organic soils over the last 25 years.
6. Loss of productivity due to prolonged cultivation of the same crops, which usually results in infestation by pests and diseases, and physical compaction.
7. Re-digging of ditches and replacement of drainage tiles necessitated by subsidence.
8. Higher rates of fertilizer applications. Some producers mentioned increases of the order of 25 to 50%. Of course, the densification and mineralization of the soil with time is partly responsible for the increases.
9. Increased difficulties in soil management due to the heterogeneity of the worn down soils.
10. Limitation of crop choice.
11. Closer control of irrigation becoming necessary to prevent excessive leaching of nutrients or formation of a compact layer at the surface.
12. The necessity to adopt new cultural practices to counteract the adverse effects of soil shallowness.
13. Crop rotation becomes essential to prevent loss of productivity.

14. Complex management of weed and pest control measures due to uneveness of plant growth in the fields with mineral islands.
15. The occurrence of stony and gravelly sub-soils imposes costly hauling out of undesirable mineral materials following re-digging of ditches.
16. Increased frequency of machinery breakdowns and repairs as mineral sublayers are progressively reached, because the specialized equipments adopted for organic soils are less rugged.

All these problems are real; however, very few scientific data exist to substantiate these and to allow a proper assessment of the situation. Therefore, a need exists for the gathering of basic data on the use and management of organic soils.

PHYSICAL, CHEMICAL, BIOCHEMICAL AND MICROMORPHOLOGICAL CHANGES

Earlier workers (van Heuveln et al. 1960, Jongerius and Pons 1962, van Heuveln and De Bakker 1972, Dömsödi 1980), mainly the Dutch who have reclaimed, used and managed organic soils for a long time, described soil formation processes in organic soils, and proposed a scheme for what they called the "progressive soil formation". Depending on the kind of parent materials and the environmental conditions, mull (more favourable) and moder (less favourable) soil formations occured. It is noteworthy that, in Europe, the soil-forming processes were greatly influenced by man and the special peat management techniques such as claying, sanding and mineral matter admixing practiced there. Basically, the soil-forming processes in peat are more or less the same as those which are at play in mineral soils.

Hammond et al. (1982) were able to show, using micromorphological techniques, the relationship between the microfabrics and the physical and chemical properties (bulk density, pH, water holding capacity, ash content) of soils under amelioration and management for more than 100 years. Thus, the mullicol O-fabrics which are usually associated with good productive organic soils came about as a result of the disintegration process which leads to a homogenisation of the soils. This illustrates the fact that considerable time is required for an organic soil to reach such a state of development from raw peat materials.

There is a large consensus about the general changes of organic soils brought about by cultivation. Thus, cropping and continuing cultivation result in increases in bulk density, ash content, pH, total N, contents of P, K, Ca, Mg and most metal ions, C.E.C, humification index, humic substances, lignin, bitumen and microbial activities; and decreases in total carbon, cellulose, hemi-cellulose, maximum water holding capacity, total porosity, carbon:nitrogen ratio and rubbed fiber content (Eigen 1961, Filippenko 1954, Frecks and Puffe 1958, Colyakov 1959, Jasmin et al. 1981, Kuntze 1976, Lévesque et al. 1982 and 1987, Lucas 1982, Lupinovick 1968, Njos 1978, Peterson et al. 1945, Townsend and MacKay 1963). Authors are at variance on some aspects but it should be noted that specific cultural and management practices would influence the overall effect of cultivation on several properties such as N level, porosity and water holding capacity. Furthermore, most of these changes do not extend

beyond the plough layer (Staker and Jornlin 1945, Lévesque et al. 1982). According to Pessi (1961), the loss of peat characteristics after long-term cultivation would be caused by the increase in the ash content in the arable layer. One cannot ignore this aspect in the soil aging process, but the continued and long lasting process of humification and mineralization would have an over-riding influence on organic soils transformations (Mathur and Farnham 1985), although new virgin material is continually brought up from sublayers and mixed into the plough layer due to subsidence.

In a recent study involving fields cropped from 0 to 15 years, Lévesque et al. (1982) found that the chemical changes related to humification and mineralization were restricted to the plough layers while the physical changes were manifest at lower depths in the soil profiles. The establishment of synchrony between subsurface layers by a palynological approach was a key element in this study (Mathur et al. 1982). It was found more recently (Dinel et al. 1987) that cultivation did bring out chemical changes in the whole profile of dyked marsh soils but it was shown that these changes had resulted from the downward movement of partly degraded fine organic materials. These data emphasize the fact that measures for controlling the long-term subsidence of cultivated organic soils should be aimed at the surface layer as that is where most of the biochemical oxidation occurs.

HUMIFICATION AND SUBSIDENCE OF ORGANIC SOILS

All economic usages of peatlands require drainage. The removal of water causes aeration of the peat. In the context of agricultural usage, the resultant surge in decomposition and humification is further accelerated by the liming, fertilization and tillage needed for growing crops. Bramryd (1980) among others has assessed the impact of the decomposition and humification of drained peatlands on the global carbon and nitrogen cycles to be considerable. As the humus produced is more compact than the undecomposed plant residues, humification also contributes to the loss in volume of the organic deposit. The loss manifests itself as a slow but continual decline in surface elevation of the cultivated soils by 1 mm to 7 $cm.y^{-1}$. This phenomenon is called subsidence, and offers a good perspective for considering the relative effects of various factors that influence the rate of humification in peatlands (Mathur 1982).

Peats richer in cellulose decompose faster and to a greater extent than woody peats. As climate influences all biological processes, Eggelsman (1976) found that within a group of low moors, the subsidence rate was correlated with the Lang factor (mm annual precipitation/mean temperature in °C). Maintining a high water table in a managed peatland helps to reduce humification and subsidence as the water curtails the amounts of air in soil pores. The level at which water table may be maintained safely and conveniently is partly determined by the type of crops grown. The crop choice also influences the level to which soil pH has to be raised by liming. Microbial decomposition, and concomitant humfication, are at their maxima at or near neutral pH. Frercks and Puffe (1959) noted that about 50% of the increase in the rate of decomposition due to rising pH is between pH 4 and 6. Most agricultural crops require a soil pH above 5.0 or 5.5, although

acceptable yields could be achieved at lower pH's with certain crops (Lévesque and Mathur 1983, Mathur and Lévesque 1983). As decomposition and humification progress, and the peat becomes denser, the voids between soil particles tend to become smaller. Such micropores are more apt to be anaerobic than macropores, and therefore the lack of oxygen slows down humification with time. The lack of oxygen can also occur if root density in soil is high as under grass. Peat soils evolved with grass tend to decompose and subside less than those under row crops (Schothorst 1977, Lévesque et al. 1987).

The humification and resultant subsidence threaten to phase out of present highly economic usages vast areas of cultivated organic soils in Canada, U.S.A. and elsewhere (Stephens and Speir 1970, Mathur 1982). As soils decompose, humify and subside, the increasing humus content provides sites for tight complexation of some essential micronutrients and retention of various pesticides used for crop protection. In addition, the water holding capacity and hydraulic conductivity of the soils decrease because humified peats are more compact and retain less water than raw peats. Soil subsidence also necessitates periodic intensification of the drainage systems, and protection of the fields against flooding from surrounding higher ground or water bodies.

MEANS OF PROLONGING THE USEFUL LIFE OF ORGANIC SOILS

If the degradation, decomposition and subsidence of cultivated organic soils are inevitable because of their inherent organic nature, there are means of retarding the disappearance of the organic soils, whether by management practices or by innovative biological and chemical interventions.

Maintaining a higher water table in the fields is the most obvious method for slowing down humification and subsidence because water excludes air that promotes bio-oxidative decomposition, as well as water gives buoyant support to the surface layer. However, since this method is not entirely safe, the water tables are generally not maintained as high as would be necessary to curtail the decomposition substantially.

Overlaying of sand on peat pastures, as practiced in Europe, helps reduce subsidence. The water table can be kept at the mineral-organic interface while the sand is able to bear the weight of cattle. In certain fen peats used for growing cereals, fields are kept flooded from fall to spring to permit sedimentation of mineral matter from river water. This mineral matter is then mixed into the organic layers, thus helping stabilization of the humus.

Incidentally, for certain crops, admixing of organic overlay with the mineral sub-soil constitutes an ameliorative practice for most shallow organic soils whenever and wherever feasible. This practice is widely used in Germany, Holland and East Anglia where sand is of common occurence as mineral substratum of vast areas of peatlands (Kuntze 1980, Wind and Pot 1976, Smith 1969). In Canada, sand substratum is not so common, and several other types of mineral and limnic sub-layers are found; some of these materials could create problems at times. In a recent study (Lévesque et al. 1988), we showed that various mineral sublayers generally

improved on admixing with organic overlays. Significant losses in short-term productivity of the organic overlays can be avoided by limiting the volume/volume contribution of the mineral sublayer to about 25% at the outset, particularly when the sublayer is a clay. Co-occurence of gyttja and shell layer is not injurious to the agricultural capability of an organic soil as the presence of gyttja alone. Among improvements brought about by admixing of organic overlay include structural amelioration of the mineral sublayers.

The humification and subsidence of cultivated organic soils can be retarded by about one-half by gradual addition of copper (5 to 15 $kg.ha^{-1}.y^{-1}$) to attain and maintain copper concentrations of 100 to 400 $\mu g.g^{-1}$ in soils with bulk densities of 0.1 to 0.4 $g.cm^{-3}$ (Mathur 1982, Mathur and Lévesque 1983). We have shown that such levels of Cu needed are many times lower than those which have been established as giving any environmental or agricultural problems (Mathur 1987). The copper inactivates degradative soil enzymes which determine the rate of decomposition of their organic milieu.

SELECTION OF CRITERIA FOR ESTABLISHING AGRONOMIC VALUE OF ORGANIC SOILS

In the selection of suitable criteria for assessing the agronomic value of organic soils, one may use the approach followed in a recently proposed capability classification system (Mathur and Lévesque 1987) where 7 factors served as basic elements. Five of these factors (Table 1) are directly related to the inherent properties of peat materials; in fact, these factors or criteria could be used in connection with soil quality.

These are:

- degree of decomposition in the context of botanical composition
- wood content
- reaction (pH)
- depth of deposit
- underlying materials

(a) Degree of decomposition in the context of (botanical composition)

This criterion receives much emphasis in the taxonomic classification of peats, because the degree of decomposition correlates with a series of other properties that influence potential productivity, namely, density, water holding capacity, porosity, hydraulic conductivity, bearing capacity, cation exchange capacity, etc.

A mixed peat with sphagnum moss, some wood and sedge is more desirable than a peat made of sphagnum alone. Compared to Mesisols and Humisols, Sphagno-Fibrisols have lower bearing capacity, are more prone to subsidence, slower to warm up, harder to drain, poorer in nutrients and more acidic, but have higher porosity and water holding capacity. The Humisols have low permeability, very low hydraulic conductivity, but higher exchange capacity and ion retention.

The amounts of fertilizer-N required for growing vegetables in Sphagno-Fibrisols would be about 5 times of those required for the same purpose in Mesisols or Humisols. But, in truck farming, the cost of additional N required is a small portion of the total economic input. The

Fibrisols are generally poorer in Cu, Fe, Mn and Zn than other organic soils (Lévesque and Mathur 1986). However, our recent studies on a large population of soils suggest that the plant-availability of these elements in the Fibrisols is good to excellent due to lack of humus-related specific site of complexation (Mathur and Lévesque 1988, Lévesque and Mathur 1988). The impression that Sphagno-Fibrisols require more lime is based on the knowledge that their pH is generally low. However, as their bulk density is also low, the total lime required may not be exceptionally high. So, the limitations of Sphagno-Fibrisols with respect to agronomic value and soil quality may not be as severe as have been believed to be. However, the possibility that they may be improved by plastic mulching, as indicated by our preliminary work, needs to be researched further.

(b) Wood content

Presence of stumps and logs is a physical hindrance to reclamation and cultivation, although some disagreement exists about what constitutes unacceptable quantities; the resistance to decomposition (hardness) of the wood has to be considered, as well as the depth at which it is found.

It remains that wood becomes a problem when it is at surface when it detracts from uniform seeding and germination, and causes frequent interruptions and occasional breakdowns of machinery used for harvesting of under-ground produces. On the other hand, wood below the plough layer contributes positively. It has acceptable permeability, shrinks less by drying and compression, and decomposes and subsides more slowly than most other materials. It follows that wood that is present throughout the profile or near the surface would pose more intense and longer lasting problems than that which is present in the lower part of the control section.

(c) Reaction (pH)

Nutrient availability is adversely affected by both low and high pH values. However, the high lime requirements advocated at low pH's may not be so high in reality because organic soils at pH 3 and 4 would be less dense and therefore, on a weight basis, there would be less mass to lime. It is noteworthy that several crops (potatoes and grass crops) can be avantageously grown at about pH 4.0 in organic soils. Furthermore, because the C.E.C. of these soils is high, more Ca is plant-available in an organic soil than in a mineral soil even at similar levels of base saturation (Lévesque and Mathur 1983, Mathur and Lévesque 1983). Also, in organic soils (lacking aluminosilicates) even at pH 4.0, soluble Al is not present at phytotoxic levels.

(d) Depth of deposit

Thickness of an organic soil is of paramount importance in the long-term utilization of that soil. The 80-cm surface layer is normally above the water table in a cultivated soil and is vulnerable to biodegradation and shrinkage. The nature of the material between 80 and 200 cm affects water movement and influences choice of the drainage system required. A peat deposit of >200 cm depth should allow productive agriculture for at least 50 years. Shallower soils may be uneconomic for reclamation.

(e) Underlying material

The nature of the underlying mineral material is also an important consideration in long-term planning, especially for possible continued use after most of the peat has disappeared. For obvious reasons, if the substratum is made of gyttja rich in reduced sulfur, gravel or bedrock, there would finally be little left that is of agronomic value. It is true that overlying shallow organic soils with a sandy subsoil would tend to dry out while a compact clay sublayer would cause a perched water table. However, one should recognize that admixing organic overlays with most underlying materials is an ameliorative practice, producing tilths that are quite suitable for cereal and vegetable productions (Lévesque and Mathur 1985).

SELECTION OF CRITERIA FOR MONITORING AGRONOMIC QUALITY OF ORGANIC SOILS

The criteria examined in the last section could be successfully used for assessing both agronomic potential and changing quality of organic soils. However, in terms of agricultural usage, soil quality should be put or measured in a dynamic context that could indicate in both the short- and long-terms how a soil evolves, changes or resists degradation. The criteria should reflect the gains and losses under various management practices, and also should show how sustained productivity could be economically achieved and rendered predictable under specific conditions of climate and crop choice.

At present, the data required for a selection of such criteria are scarce and fragmentary, which points to the need for data acquisition through the monitoring of a variety of organic soils. The monitoring should be oriented towards the changes which have a real impact on the following: the capacity of organic soils to store and supply water and nutrients; to transmit water; to exchange gases; to respond to any physical, chemical and environmental modifications; to adapt to new cultural and management practices, and to produce and maintain acceptable crop yields. In that connection, a recent study (Mathur and Lévesque 1989) indicated that the quality of organic soils in terms of ability to store and cycle water and nutrients, declines with length of cultivation, even before nutritional and water management problems arise, probably due to poor soil aeration.

In table 2, we have grouped properties, measurements of which are likely to yield useful information on the nature and dynamic state of cultivated organic soils. Some of these properties are more inclusive in character (such as degree of decomposition); some others are better indicators of soil changes, modifications or evolution. A tentative assessment of the various properties was made in that respect (Table 2).

There is a general agreement about the fact that the degree of decomposition of a peat material is considered as the prominent feature of all aspects of natural and economic roles of organic soils. Indeed, with the exception of the aggregation state and possibly pH, the sixteen properties or features listed in table 2 are directly related to or depend on the state of decomposition of the peat materials. Mathur and Farnham (1985) have clearly shown that connection while discussing the various

means of measuring the extent of humification or degree of decomposition of organic soils.

Ideally, measurements of all 16 properties should be obtained from typical and representative soils. The measurements made on cultivated soils should be weighed against the yield performance of these soils. The monitoring should be carried out over a period of several years, long enough to allow conclusive results. It may not be feasible or even possible to carry out all measurements on all the desirable soils and crops. At least, the work should be carried out far enough to provide a basis for proper selections of criteria. It is hoped that, early enough after the initial period of monitoring, a few dependable indicators will come out to allow a more selective and restrictive monitoring.

CONCLUDING REMARKS

It is recognized, and this has been shown in the above sections, that some information, albeit fragmentary, is available on peat evolution, changes under cultivation, losses and gains through various cultural and management practices. Here, however, the particular aim in carrying out the measurements and monitoring on organic soil properties is to find out where and when a potential soil limitation begins to manifest itself through a decline in crop performance. For instance, when does a crop begin to show a reduction in yields due to a lack of depth? In the same connection, what are the associated implications in term of soil quality? etc. True enough, there is a real need for good basic data to define soil quality in a sound and practical manner as well as to provide convenient and dependable means of assessing it in the context of sustained soil productivity.

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Table 1. A Modified Guide for the Capability Classification of Organic Soils (Mathur and Lévesque 1987)

Factors		Penalty Points
1. Decomposition		
	% Rubbed Fiber	
Fibric	>60% mostly Sphagnum	25
	40 to 60% mostly Sphagnum	20
	40 to 60% not mostly Sphagnum	10
Mesic	20 to 40% any material	0
	10 to 20% " "	10
Humic	<10% " "	20
2. Wood Content		
	Volume % Wood in tiers	
None		0
1 to 25%	below 80 cm	5
1 to 25%	above 80 cm	10
25 to 50%	below 80 cm	10
25 to 50%	above 80 cm	20
>50%	below 80 cm	20
>50%	above 80 cm	35
3. Reaction		
	pH	
<3.5		20
3.5 to 5.0		10
5.0 to 6.5		0
6.5 to 7.5		10
>7.5		20
4. Depth of Organic Deposit		
>200 cm		0
120 to 200 cm		10
80 to 120 cm		20
<80 cm		30
5. Underlying Materials of >20 cm Thickness within 3m		
Silt, loam		10
Sand		15
Clay		20
Gyttja, coprogenous or sedimentary peat without adjacent mark or shell-rich layer		50
Gyttja, Coprogenous or sedimentary peat with adjacent >20 cm shell-rich or marl layer		10
Marl or Shell-rich layer		10
Bedrock		50
Stoniness (<10%) in the mineral sub-layer		5
Gravel, or >30% stones in any sublayer		30

Table 2. A proposed list of critieria useful in monitoring the agronomic quality of organic soils.

(*** = more suitable)
(* = less suitable)

Criteria	Indicator Suitability	Short- Medium - or Long-term
1. Degree of decomposition: - % rubbed fibers - PP index	***	M
2. Ash content	*	M
3. Reaction (pH)	*	S
4. Bulk density	**	M
5. Bearing capacity	*	M
6. Carbon: Nitrogen (Ratio)	**	S
7. Subsidence: - rate of subsidence - loss of relative elevation	**	M
8. Rate of respiration	**	S
9. Phosphatase activity	**	S
10. Sugar content: Total carbon (Ratio)	*	M
11. Aliphatic C: Phenolic C (Ratio)	*	M
12. Calorific value	**	M
13. Water holding capacity	***	S
14. Hydraulic conductivity	**	S
15. Porosity - Macro- : Micro-pores (Ratio)	***	M
16. Proportions of fine materials	***	S
17. Micromorpholgical aspects: (Ratio) - Amorphous: structured materials - Monomorphic: heteromorphic mat.	**	L
18. Aggregation state: coalescence of humic materials	**	L

SOIL ORGANIC MATTER AND SOIL QUALITY

M. SCHNITZER

1. Introduction

Soil organic matter (SOM) refers to the sum-total of all organic carbon-containing substances in soils. The organic carbon content of soils ranges from <0.1% in desert soils to close to 100% in organic soils. A typical Canadian agricultural soil may contain 2-5% organic matter in the top 15 cm.

SOM consists of a mixture of plant and animal residues in various stages of decomposition, of substances synthesized microbiologically and/or chemically from the breakdown products, and of microorganisms and small animals and their decomposing remains (Schnitzer and Khan, 1972). To simplify this very complex system, SOM can be subdivided into: (a) non-humic, and (b) humic substances.

Non-humic substances include those with still recognizable chemical characteristics such as carbohydrates, proteins, peptides, amino acids, purines, pyrimidines, fats, fatty acids, alkanes, waxes, resins, pigments and other low molecular-weight organic compounds. Generally, these compounds are relatively easily degraded in soils and have short life spans.

The bulk of SOM, however, consists of humic substances. These are amorphous, mainly hydrophilic, chemically complex, polyelectrolyte-like materials, which range in molecular weights from a few hundred to several thousand (Schnitzer, 1978). Humic substances no longer exhibit specific physical and chemical characteristics normally associated with well-defined organic compounds but are more resistant to chemical and biological degradation.

Before turning to the effects of SOM on soil quality, it may be appropriate to describe the chemical composition of this material.

2. Composition of SOM

The following are estimates of the average composition of SOM in a typical mineral Canadian soil: carbohydrates - 10%; N-compounds (including proteins, peptides, amino acids, ammonia, purines, pyrimidines and unidentified N-substances) - 10%; alkanes, fatty acids, fats, waxes, resins etc. - 10%; and humic substances (humic acid, fulvic acid, humin) - 70%. These figures may vary depending on local conditions.

In the following paragraphs each group of major constituents will be discussed in greater detail.

2.1 Carbohydrates

Carbohydrates in SOM occur mostly as polysaccharides (Cheshire, 1979). The latter, on acid hydrolysis, produce hexoses (glucose, galactose, mannose), pentoses (arabinose, ribose, xylose), deoxyhexoses

(fucose and rhamnose), uronic acids (glucuronic and galacturonic acids) in addition to small amounts of fructose and methyl sugars (2-O-methyl-L-rhamnose and 4-O-methyl-D-galactose). Small amounts of sugar alcohols (mannitol and inositol) have also been identified. Hydrolyzates of SOM usually also contain the two amino sugars glucosamine and galactosamine and sometimes also trace amounts of muramic acid (Cheshire, 1979; Stevenson, 1982).

Aside from trace amounts of sugars which are soluble in water, the carbohydrates are not readily isolated from soils because of their intimate association with non-carbohydrate components. Whether the carbohydrates constitute a heterogeneous mixture of different polysaccharides containing different sugars or whether they consist of a single homogeneous but complex polysaccharide containing different sugars is not known at this time. Their origins are plant and animal residues, extracellular gums produced by microorganisms and their cellular tissues (Cheshire, 1979).

Of all SOM components, polysaccharides are most readily available as a source of energy to microorganisms.

2.2 Nitrogenous components

Nitrogen is the only essential nutrient which does not originate from the weathering of minerals; its source is the atmosphere where it is the predominant gas (79%) (Schnitzer, 1985). Only a few microorganisms have the ability to use molecular N_2; all remaining living organisms require combined N for carrying out their life activities. Gains in soil N occur through fixation of molecular N_2 by microorganisms and from the return of ammonia and nitrate in rain water. Losses occur through crop removal, leaching erosion and volatilization. The conversion of molecular N_2 is brought about by biological nitrogen fixation. Organic forms of N, in turn, are converted to NH_3 and NO_3^- by ammonification and nitrification, respectively. Nearly all of the soil-N is combined or closely associated with SOM. The average N distribution in a typical Canadian SOM is: amino acid-N: 30%; amino sugar-N: 3%; ammonia-N: 23%; N in purines and pyrimidines: 2%; unidentified N: 42% (Schnitzer, 1985). Assuming that ½ of the NH_3-N originates from complex N-containing structures, 53% of the total N in the SOM remains unidentified. There are recent indications that some of the unidentified N is present in heterocyclic rings in the SOM. The importance of N in soils is clearly related to it being a significant constituent of proteins, nucleic acids, porphyrins, and alkaloids. It remains a source of concern that roughly half of the organic N in many agricultural soils occurs in unknown forms, so that a major future research need is the detailed identification and characterization of the unidentified soil-N.

2.3 Alkanes and fatty acids

SOM contains a diverse group of lipids which range from simple alkanes and fatty acids to sterols, terpenes, chlorophyll, fats, waxes and resins (Stevenson, 1982). Lipids are hydrophobic and thus have the potential for altering soil physical properties. Supercritical gas extracts of soils with n-pentane contain long straight-chain n-alkanes and cyclic alkanes (Schnitzer et al., 1986). The major components, however,

are long-chain normal, branched, unsaturated, hydroxy and dicarboxylic fatty acids of microbiological origin. ^{13}C NMR spectra of different types of SOM show the presence of significant concentrations of aliphatic structures which could include complex waxes.

2.4 Humic substances

These are amorphous, dark coloured, partly aromatic, mainly hydrophilic, chemically complex polyelectrolyte-like materials that constitute most of the weight of SOM.

Based on their solubility in alkali and acid, humic substances are usually partitioned into the following three fractions: (I) HA (humic acid), which is soluble in dilute alkali but is coagulated by acidification of the alkaline extract; (II) FA (fulvic acid), which is that humic fraction which remains in solution when the alkaline extract is acidified, that is, it is soluble in both dilute alkali and dilute acid, and (III) humin, which is that humic fraction which cannot be extracted from the soil by dilute base or acid (Schnitzer, 1978; Stevenson, 1982). Chemically, the main differences between HA and FA are that HA contains more C and N but fewer CO_2H groups and less O and has a greater molecular weight than FA. There is relatively little difference between the two materials in H and S contents and in concentrations of phenolic OH, C=O and OCH_3 groups. From data published in the literature and from more recent ^{13}C NMR data it appears that the analytical characteristics of humins are similar to those of HAs.

Extensive chemical and sprectroscopic studies suggest that between 50 and 60% of the weights of humic materials consist of aromatic structures heavily substituted by CO_2H and OH groups (Schnitzer, 1978). These structures associate through relatively low-energy bonds to form a network on which alkanes, fatty acids, carbohydrates and nitrogenous components are adsorbed. The outstanding features of the humic structure are its molecular flexibility and its ability to interact via oxygen-containing functional groups with other inorganic and organic soil constituents. Thus, humic substances are good naturally occurring complexing agents, have relatively large and reactive surfaces, are excellent dispersants and can act as oxidizing as well as reducing agents. Compared to biopolymers (carbohydrates and proteins), humic substances are more resistant to biodegradation in the soil. This stability is related to the complicated structural arrangement of these materials and which seems to protect them against extensive enzymatic hydrolysis. Additional stability comes from complex formation of humic substances with polyvalent cations and from adsorption on clay minerals.

2.5 Phosphorus and Sulfur

Other plant nutrients associated with SOM are P and S.

P is involved in almost all significant metabolic pathways as well as being a structural component of nucleic acids, coenzymes, phosphoproteins and phospholipids (Tate, 1985). P occurs in soils in a wide variety of forms. The orthophosphate anion interacts with Al- and Fe-oxides and hydroxides, clay minerals, solid carbonates, and SOM. Small

amounts of condensed P of mainly microbial origin are found as pyrophosphate and higher polyphosphates. Between 20 and 70% of the total soil P in surface horizons of most soils is in organic forms. Prominent organic forms are esters of phosphoric acid and inositol hexa- and pentakis- phosphates. In addition, smaller amounts of phospholipids and nucleotides are also found in soils. Apart from traces of sugar phosphates, phosphoprotein, and glycerophosphate, and small amounts of phosphonate, the chemical nature of at least 30% of the organic P still remains to be identified (Tate, 1985). It is likely that unidentified organic P occurs in insoluble complexes with clay minerals, hydrous oxides and SOM.

It appears that mineralization of organic P is a prerequisite for its availability to plants. Some forms of organic P recently identified by ^{31}P NMR include orthophosphate diesters but not orthophosphate monoesters. Mineralization of organic P to inorganic P is brought about by microbes and enzymes. Higher phosphatase activities are usually encountered in the rhizosphere because of higher microbial populations and the presence of plant phosphatases. Also, plants employ other means such as root branching, root hairs, and symbiotic relationships with mycorrhizal fungi to extract P from the soil. The importance of organic P is illustrated by recent estimates of the average annual rates of mineralization of organic P in three English arable soils which indicate that about 1/3 of the average P removal by crops could be provided by SOM by mineralization (Chater and Mattingly, 1979). Earlier estimates were that the SOM in British arable soils could supply 6 kg P ha^{-1} while for grassland soils 15 kg P ha^{-1} could be supplied from mineralized organic P. (Gasser, 1962). The mineralization and immobilization of P in soils are major biological processes which control its availability to plants.

The S content of soils ranges from 0.002 to 3.5% (Scott, 1985). Plants require the element for the production of protein, vitamins, chlorophyll, glycoside oil, and structurally and physiologically important sulfide linkages in cell walls and sulfhydryl groups. Alfalfa requires 1 part of S for every 11-12 parts of N for maximum crop yield (Biederbeck, 1978). Plants obtain S primarily from the soil as dissolved sulfate and, to a lesser extent, from the atmosphere by foliar absorption of SO_2. The S cycle resembles the N cycle in having an important atmospheric component and in being associated with SOM, but it differs in that the major source of plant available S is the weathering of minerals (Biederbeck, 1978). Over 90% of the total S in most non-calcareous soils is present in organic forms. The latter are differentiated into:

(a) Organic S that is reduced to H_2S on treatment with HI. This includes sulfate esters and ethers in the form of phenolic sulfates, sulfated polysaccharides, choline sulfate and sulfated lipids and is considered to be the most labile form of organic S.

(b) Organic S that is reduced to inorganic sulfide by Raney Nickel. This fraction seems to consist mainly of S-containing amino acids such as cysteine and methionine.

(c) Organic S that is not reduced by either HI or Raney Nickel and is considered to occur in the form of highly resistant C-S bonded compounds.

The main sulfate forms in calcareous soils are water-soluble Mg-, Ca- and Na- sulfates. The principal factors affecting the adsorption of sulfates in soils are pH, Fe and Al oxide content and sulfate concentration. Often sulfates are found as coprecipitated and cocrystallized impurities of $CaCO_3$ which are insoluble. Only water-soluble and adsorbed sulfates appear to be available to crops.

S transformations in soils result primarily from microbial activities although chemical oxidation is also possible. The major microbial processes are (Scott, 1985):

(a) Mineralization - the breakdown of large organic S-containing molecules to smaller units and finally to inorganic sulfate.

(b) Immobilization - the conversion of simple inorganic S-containing molecules to organic S-containing compounds.

(c) Oxidation - the conversion of inorganic S compounds of lower oxidation state to sulfate.

(d) Reduction - the reduction of sulfate and intermediate compounds to sulfide.

The burning of fossil fuels is adding increasingly large amounts of S to the atmosphere. Most of this anthropogenic S enters the atmosphere as SO_2. About ½ of the SO_2 is oxidized and deposited by rainfall as H_2SO_4 while the remainder is deposited in the dry form onto vegetation, soil or water at the earth's surface either by direct adsorption of the gas or in particulates. The SO_2 is oxidized subsequently. Atmospheric S can have serious environmental effects because it is localized in high concentrations. There have been reports of direct toxic effects of high SO_2 concentrations on vegetation, or indirect effects of acid rain on aquatic and terrestrial biota. Most of the concern for the environment seems to be over the acidity arising from extra S input, although N-oxides also contribute up to 30% of the acidity in rainfall. The S and N themselves may be beneficial to soils and were it not for the atmospheric input, considerable extra amounts of S and N would need to be added to the soil to obtain optimum crop growth (Scott, 1985).

3. Effects of SOM on soil quality

SOM exerts three major effects on soil quality. These are:

(a) physical effects which concern soil aggregation, erosion, drainage, tilth, aeration, water holding capacity, bulk density, evaporation, permeability, mechanical properties etc.

(b) chemical effects which relate to exchange capacity, metal complexing, buffering capacity, supply and availability of N, P, S and micronutrients, adsorption of pesticides and other agricultural chemicals etc.

(c) biological effects which are involved with activities in the soil of bacteria, fungi, actinomycetes, earthworms, roots, root hairs, soil biomass etc.

Each of these effects will be discussed in greater detail on the following pages.

3.1 Physical effects

Intensive forms of agriculture tend to reduce the SOM content thereby harming soil structural characteristics such as pore size, aggregate size, aggregate stability and increasing susceptibility to compaction and consolidation on exposure to wetting and drying. The deterioriation of soil structural characteristics leads to decreases in productivity by restricting root growth, soil aeration and drainage. The ideal soil structure would be a loose, friable and porous assemblage of aggregates which would permit free movement of water and air, easy cultivation and planting, and unobstructed germination and root growth.

Soil structure may be defined as the size and arrangement of particles and pores in soils (Oades, 1984). A good soil structure for plant growth can be characterized in terms of the presence of pores for storage of water available to plants, pores for the transmission of water and air, and pores in which roots can grow. Ideally, most of the clay fraction in a tilled soil should be flocculated into microaggregates (<250 mμ) and these microaggregates and other particles bound together into macroaggregates (>250 mμ). The majority of the macroaggregates should have diameters in the range of 1 to 10 mm (Oades, 1984). The breakdown of macroaggregates on wetting due to entrapped air and unequal swelling has been termed slaking. Slaking causes a reduction in the infiltration of rainfall or irrigation water and in hydraulic conductivity and affects the stability of microaggregates.

Processes which induce aggregation tend to bring soil particles into closer packing and allow soil binding agents to cement particles into discrete units. The binding agents may be inorganic or organic.

3.1.1 Inorganic binding agents

Clay may bind particles into aggregates but such aggregates are unlikely to maintain their integrity when wetted. Hydrous oxides of iron and aluminum cement particles together into water-stable aggregates with diameters >100 μm, especially in soils which contain more than 10% sesquioxides. Highly disordered aluminosilicates and calcium carbonate also act as cementing agents. The effectiveness of calcium carbonate may be due, in part, to relatively high concentrations of Ca in the soil solution which limit dispersion and swelling.

3.1.2 Organic binding agents

In the surface layers of many agricultural soils, SOM appears to play a major role in binding aggregates. Tisdall and Oades (1982) classify organic binding agents as transient, temporary and persistent.

Transient binding agents are decomposed rapidly by microorganisms and include microbial polysaccharides produced when various organic materials are added to the soil as well as polysaccharides associated with roots and the microbial biomass in the rhizosphere. Polysaccharides are

produced and decomposed rapidly and are connected with large (>250 μm diameter) transiently stable aggregates. Polysaccharides may be protected from microbial oxidation by associations with metal ions, tannins, humic materials or by sorption on clay surfaces and so become persistent for several years. The significance of polysaccharides as glues in soil aggregation has been pointed out on many occasions (Cheshire, 1979; Tisdall and Oades, 1982; Oades, 1984; Stevenson, 1982). Many microorganisms produce exocellular mucilages or gums which are dominantly polysaccharide. However, it is clear that in some soils, other organic binding agents or even inorganic cements are active (Tisdall and Oades, 1982). This is especially true for aggregates >50 μm diameter. Also, polysaccharides are less important as binding agents in soils rich in organic matter.

Temporary binding agents are roots and hyphae, particularly vesicular-arbuscular mycorrhizal hyphae (Tisdall and Oades, 1982). Such binding agents build up in the soil within a few weeks or months as the root system and associated hyphae grow and persist for months or years and are affected by the management of the soil. Roots not only supply decomposable organic residues to the soil and support a large microbial population in the rhizosphere but are also binding agents themselves. They enmesh fine soil particles into stable macroaggregates even after the root has died. Residues released into the soil by roots are in the form of fine lateral roots, roothairs, sloughed-off cells from the root cap, dead cells, mucilages, lysates and volatile and water-soluble materials. Plants may also increase water-stable aggregation of soils indirectly by providing food for soil animals such as earthworms and the mesofauna, enabling large populations to build up. Earthworms may stabilize structure by ingesting soil and mixing it intimately with humified organic materials in its gut. Fungal hyphae also stabilize macroaggregates. In desert soils, filaments of blue-green algae, lichens, and fungal hyphae may stabilize soils against erosion.

Persistent binding agents are degraded, partly aromatic, humic materials associated with amorphous iron, aluminum and aluminosilicates. Persistent binding agents probably include complexes of clay-polyvalent metal-organic matter, C-P-OM, and $(C\text{-}P\text{-}OM)_x$ (Edwards and Bremner, 1964), both of which are <250 μm in diameter (Tisdall and Oades, 1982). These binding agents are probably derived from resistant fragments of roots, hyphae, bacterial cells and colonies (i.e. temporary binding agents) developed in the rhizosphere. SOM is believed to be the center of the aggregate, with particles of fine clay sorbed onto it rather than SOM sorbed onto the clay surface (Tisdall and Oades, 1982). Also, among persistent binding agents are polysaccharides and organic materials stabilized by association with metals, hydrous oxides and/or clay minerals.

3.1.3 Organization of aggregates

A prerequisite for the formation of water-stable aggregates is the flocculation of clay particles into domains. SOM links the domains into microaggregates (Oades, 1984).

Edwards and Bremner (1967) suggest that macroaggregates (>250 μm diameter) consist of complexes of clay-polyvalent metal-organic matter (C-P-OM), where the clay is bonded to humified organic matter through

polyvalent metals. Particles of C-P-OM and $(C\text{-}P\text{-}OM)_x$ form micro-aggregates [(C-P-OM)x]y which are <250 µm diameter. Bonds of C-P-C and OM-P-OM and even of iron and aluminum oxides or hydrogen bonds may also occur. Tisdall and Oades (1982) propose a model for the organization of aggregates in which there are four stages of aggregation: <0.2 µm → 0.2-2µm → 2-20 µm → 20-250 µm → >2,000 µm.

Water-stable particles <0.2 µm in diameter are often floccules where individual clay plates come together to form a fluffy mass. Some particles are aggregates of very fine materials held together by SOM and iron oxides. SOM is held firmly on the clay surfaces. Aggregates are built up from structural units of various sizes and held together by binding agents.

Water-stable aggregates 2-20 µm in diameter consist of particles <2 µm in diameter bonded together strongly by SOM. Elecron micrographs of soils or thin sections of soils show individual bacteria or colonies of bacteria surrounded by a capsule composed of carbohydrates, nitrogenous and fatty substances, to which fine clay is firmly attached. These aggregates are formed from live bacterial cells and clay particles. This explains why a large part of the microbial biomass is present in the silt fraction. Since only about 2% of SOM consists of the biomass (Jenkinson and Rayner, 1977) silt-sized aggregates containing living bacteria must be newly formed. After the death and decay of the bacteria, characteristic fibrous components of the bacterial capsule remain and these also bind clay particles. Fragmentations of fungal hyphae can lead to small aggregates stabilized by fungal debris.

Aggregates 20-250 µm in diameter consist largely of particles 2-20 µm in diameter bonded together by various cements including persistent organic materials, crystalline oxides and highly disordered aluminosilicates.

Aggregates >2,000 µm are held together mainly by fine networks of roots and hyphae whose stability is controlled by agricultural practices. Inorganic binding agent are less important.

The main difference between micro- and macro-aggregates is that the formation of the former is not influenced by changes in the SOM caused by different management practices whereas the formation of macroaggregates depending largely on roots and hyphae, is controlled by management. Numbers of stable macroaggregates decline with decrease in the SOM content or as roots and hyphae decompose and are not replaced.

3.1.4. Effect of SOM on mechanical properties

De Kimpe et al. (1982) report that SOM reduces the compaction and settling of soils and that this effect is related to its relatively high water retaining capacity. They found that most of the water retention at field capacity of 21 cultivated Quebec top soils was due to the SOM rather than to the clay contents. Also, correlations between water-related parameters such as optimum water contents, liquid and plastic limits were consistently greater with SOM than with the clay content for these soils. They concluded that the two variables which control optimum dry bulk densities, that is, maximum deformability under compaction and maximum

resistance to deformability under settling of soils are controlled by SOM. Recommendations for optimum field conditions for trafficability and workability need to take the SOM content into account.

3.1.5 Water adsorption by SOM

Humic substances, the major SOM components, can adsorb large amounts of H_2O (Schnitzer, 1986). At a relative humidity (RH) of 90% 1.0 g of HA adsorbs 225 mg of H_2O, while 1.0 g of FA adsorbs 508 mg of H_2O. The adsorption mechanism consists of three stages: (a) monolayer water adsorption up to a RH of 35%; (b) adsorption of an additional H_2O layer between RHs of 35 and 60%; and (c) adsorption of additional 2 H_2O layers by HA, and 6 H_2O layers by FA, with the H_2O layers held together by hydrogen bonds at RHs >60%. The adsorption of H_2O on humic materials is cooperative, that is, the more H_2O molecules are already adsorbed, the easier it is for additional molecules to become adsorbed. The high content of oxygen-containing functional groups of humic materials, especially CO_2H groups, aids H_2O adsorption by providing many oxygens and hydrogens for hydrogen bonding with H_2O. The high retention capacity of SOM for H_2O is by many scientists (Johnston, 1982) considered as one of the most important characteristics of SOM. Well humified SOM can retain up to four times its own weight of water (Vaughan and Malcolm, 1985).

3.2 Chemical effects

3.2.1 Losses of C and N with cultivation

With intensive cultivation, the initial SOM content of soils decreases and tends to attain equilibrium or "steady state" levels that depend on the amount of organic material added, climate, man-made activities, and the soil environment (Jenny, 1941). In North America SOM "steady state" levels have so far not yet been reached. In Western Canada, after 60-80 years of cultivation, the concentration of organic C in the Ap horizon of Chernozemic soils has decreased by 50-60% and that of organic N by 40-50% (Campbell et al., 1976). Effects of breaking the Virigin Prairie sod entailed rapid decomposition of the SOM and a decline in the rate of addition of organic materials so that the "steady state" level of SOM was lowered to what was sustainable by the new ecosystem. The two reasons why farming systems and practices employed on the Canadian Prairies have led to dramatic declines in SOM were: (a) inputs to the system were less than those prior to cultivation; and (b) use of excessive tillage which resulted in accelerated erosion (PFRA, 1983). The authors of the PFRA report (1983) single out the practice of fallowing for having an especially deleterious effect on SOM levels. The report considers fallowing as an extreme form of intensive tillage which results in decreased quantities of plant residues returned to the soil, accelerated decomposition of SOM, increased leaching and dentrification, losses of mineral N released from the SOM, and accelerated losses of surface soil by wind and water erosion resulting in losses of SOM and valuable plant nutrients. Campbell and Paul (1978) showed that under fallow the net annual mineralization of N was 104 kg N ha^{-1} as compared to 52 kg N ha^{-1} under cropping on a Brown Chernozem soil. Along the same lines, Dormaar (1979) reports that up to 60% of the organic C of Ah horizons of some Prairie soils was lost under wheat-fallow systems of farming and notes that an increased frequency of fallowing in a rotation

usually results in a more rapid decline of SOM. The same phenomenon had already been noted in 1968 by Ridley and Hedlin who found 3.7, 4.9, 4.7 and 7.2% SOM after 37 years of wheat-fallow, wheat-wheat-fallow, wheat-wheat-wheat-fallow, and continuous wheat, respectively, in the Ap horizon of a Black Chernozem soil. Observations similar to those made on the Prairies have also been reported from Eastern Canada. For example, Martel and Deschenes (1976) note that compared to grassland soils, adjacent Quebec soils cultivated for 30 years lost up to 54% of their organic C and 51% of their total N, while water-stable aggregates decreased between 50-84%. To stem the excessive SOM losses, the authors of the PFRA (1983) report recommend: (1) reducing fallow; (2) extended or continuous cropping; (3) reduced tillage or zero till systems; and (4) inclusion of grasses, legumes and pulse crops in the cropping sequence.

From the available literature it becomes quite clear that current agricultural practices lead to large losses of SOM from Canadian soils. The consequences of continuous SOM losses on soil quality are serious. Below a minimum SOM level in the soil not sufficient organic matter is available to fullfill the many functions discussed in this report. The implications for crop production are quite clear: impaired chemical and physical properties, declining nutrient reserves and availability and increasing costs of producing crops.

3.2.2. SOM and cation exchange capacity

SOM in most mineral soils accounts for 30-65% of the cation exchange capacity (Campbell, 1978). The more humified the organic matter becomes, the higher is its exchange capacity. The cation exchange capacity of SOM is considerably higher than that of clay minerals. Martel and Lavadière (1976) determined cation exchange capacities of podzolic and gleysolic Ap horizons in Quebec. Cation exchange capacities of the organic matter in these samples were 161 ± 45 meq/100 g and 29.6 ± 6 meq/100 g for the clay components. Similar data for samples taken from the Ap horizon of Chernozemic soils in Saskatchewan ranged from 214-223 meq/100 g for the organic matter and 56-57 meq/100 g for the clay (St. Arnaud and Sephton, 1972).

3.2.3 Buffering capacity of SOM

Most of the buffering capacity of soils arises from their colloidal components, that is, SOM and clay minerals. The resistance to pH change is low in sandy soils but high in fine textured and organic soils. Without this buffering capacity large pH and osmotic fluctuations would occur and crops and organisms would be injured because as a result of biological activity in the soil, acids and bases are produced continuously. Also, the addition of fertilizers, pesticides and other soil amendments produces similar effects.

3.2.4 Metal complexing capacity of SOM

The stability in solution of transition elements is significantly increased by their complexation with soluble organic ligands. In the absence of such natural ligands, these elements would be removed from the soil solution by hydrolysis to insoluble forms or by adsorption onto

mineral or organic surfaces in the soil. Fe, Mn, Co, Cu and Zn undergo hydrolysis under conditions prevailing in soils (Linehan, 1985). Hydrolysis of Fe and Cu to insoluble forms, which are unavailable to plants, is likely to occur in most soils. Hydrolysis to insoluble and unavailable forms of Mn, Co and Zn will be important only in neutral or alkaline soils. Hydrolyzed species are also significant because they can sorb on solid surfaces. The most effective ligand in soil is FA which can form both water-soluble and water-insoluble metal complexes, depending on the pH, the metal to FA ratio and the ionic strength (Schnitzer, 1978). The total organic matter content of a soil is important with regard to trace metals because it defines the size of the reservoir of bound and immobilized trace metals. As SOM is mineralized, trace metals will be released into forms available to plants. On the other hand, a very high organic matter content may be problematic because the rate of metal release may be too slow for sustaining a productive agriculture. A priority in this area should be to have a relatively high concentration of FA in the soil solution which would maintain sufficient metals, including trace metals, in plant-available forms. This could be achieved by periodic additions of fresh or composted organic materials to soils.

3.2.5 Interactions of SOM with pesticides

The persistence, degradation, bioavailability, leachability and volatility of pesticides are directly related to the nature and concentration of SOM in a particular soil (Khan, 1978). Pesticides may be adsorbed on SOM and retained by van der Waal's forces, hydrophobic bonding, hydrogen bonding, charge transfer, ion exchange and ligand exchange. The rate at which an adsorbable pesticide must be applied to the soil can vary 20-fold, depending on the nature of the soil and to a large extent on the amount of SOM it contains (Stevenson, 1982). SOM can promote the non-biological degradation of pesticides and can also form strong linkages with residues arising from the partial chemical and microbial degradation of the pesticides. These processes may play important roles in the detoxification and protection of the environment. Soils continue to accumulate increasing amounts of pesticide residues which could move into bodies of invertebrates, pass into air or water, become adsorbed by plants or degraded to other products (Khan, 1980). A portion of pesticide residues is unextractable by polar and non-polar solvents and appears to be strongly retained by SOM, especially humic materials. These bound residues may contain intact pesticide molecules which, when released, could exert deleterious biological effects. On the other hand firm binding of pesticides to SOM may be a safe method of decontamination. Information as to how pesticides react with SOM provides a rational basis for their effective use and for minimizing undesirable side effects.

3.3 Biological effects of SOM

3.3.1 Soil as a living system

The slow mineralization of SOM by macro- and micro-organisms in the soil provides growing plants with supplies of essential nutrients. Soil organisms include a vast array of bacteria, fungi, actinomycetes, protozoa, yeasts, algae, earthworms and insects. In general, numbers of organisms in soils correlate postively with SOM concentrations in the upper

30-40 cm of soil (Henis, 1986). The level and composition of microorganisms may change daily with changing moisture and temperature conditions, drying and wetting, freezing and thawing, heating and cooling and fumigation. The soil may be regarded as a living system composed of many individual creatures which respire (as is evident from the O_2 uptake and the CO_2 output), digest available nutrients, release ammonia from amino acids and azide, and produce heat from the decomposition of SOM (Henis, 1986). Soil microorganisms play a major role in the formation and decomposition of SOM. Microorganisms active in the decomposition of SOM are oligotrophic heterotrophs whose activities in soils are substrate-limited. This means that these microorganisms live under a constant state of starvation. The rate of SOM degradation is lower than the rate of utilization of its products by plants and organisms. This is why only few products of degradation or mineralization accumulate although small amounts of breakdown products such as alcohols and organic acids have been detected.

3.3.2 Turnover of SOM and biomass

Jenkinson and Rayner (1977) published a model that collates data assembled over the years on the turnover of SOM in some of the classical experiments at Rothamsted. SOM is separated into five compartments: decomposable plant material (DPM, half-life 0.165 yr); recent plant material (RPM, 2.31 yr); soil biomass (BIO, 1.69 yr); physically stabilized organic matter (POM, 49.5 yr); and chemically stabilized organic matter (COM, 1,980.0 yr). For a unitary input of plant material (1 t fresh plant C ha^{-1} yr^{-1}) under steady state conditions, after 10,000 yr, the model predicts that the soil will contain 0.1 t C in DPM, 0.47 t C in RPM, 0.28 t in BIO, 11.3 t in POM, and 12.2 t in COM. The predicted radiocarbon age is 1,240 yr. The fit between predicted and measured data is sufficiently good to suggest that the model is a useful representation of the turnover of organic matter in cropped soils. After 10,000 yr the C distribution in the five fractions is: DPM - 0.41%; RPM - 1.94%; BIO - 1.15%; POM - 46.58%; and COM - 50.29%. DPM is considered the readily decomposable parts of the plant; RPM the resistant lignified plant structures; BIO the living part of SOM; POM the 10-100 yr old C; and COM the very old C. In the long run no fraction is resistant to decomposition. This process, in which losses and gains occur simultaneously is described as turnover, which may be defined as the flux of organic C through a given volume of soil. Turnover time is the amount of C in a soil when equilibrium has been reached divided by the annual input of C into that system (Jenkinson and Rayner, 1977).

The soil biomass constitutes about 2% of the total soil organic C (Jenkinson and Rayner, 1977) and includes bacteria, fungi, actinomycetes, protozoa, algae and microfauna. Usually plant roots and fauna larger than 5×10^9 μm^3, such as earthworms, are not included (Sparling, 1985). The bulk of the biomass is normally inactive because of nutrient limitations. The addition of available organic substrate to the the soil increases microbial activity and biomass. The main source of organic input is plant material in the form of roots, leaf and stem litter and root exudates. Fungi form a major component of the biomass. While the biomass makes up only a small portion of the total SOM, it is comparatively labile and has multiple roles in soils. It affects the decomposition and turnover of SOM, nutrient immobilization and cycling, root physiology and soil structure.

While the biomass-C makes up only 2% of the SOM-C, Jansson and Persson (1968) estimate that in Swedish soils about 15% of the organic C can be classified as "active" or "labile" C. They believe that it is the amount of "active" SOM component that is an important determinant of soil fertility and of the impact of agriculture on the environment. The figure suggested by Jansson and Persson (1968) roughly equals the concentration of biopolymers (carbohydrates + amino compounds + nucleic acid bases) in SOM (Schnitzer, unpublished data).

3.3.3 Physiological effects of SOM

Under laboratory conditions, humic substances can have favourable effects on the growth of higher plants as measured in terms of increases in lengths, and fresh and dry weights of shoots and roots and even by the increase in numbers of lateral roots and flowers (Vaughan and Malcolm, 1985; Rauthan and Schnitzer, 1982). Humic substances can also influence the growth of microorganisms as diverse as algae, dinoflagellates, bacteria and yeasts. The precise effects depend on the nature of the humic substance, its concentration, the composition and pH of the growth medium, the culture conditions, and the plant species under investigation. Humic substances exert direct and indirect effects. A direct effect would be the HA or FA influencing protein synthesis or photochemical reactions in plants. The HA or FA would have to enter the plant but so far only low-molecular weight FA has been shown to be taken up by plant roots and there was little translocation to the shoot. An indirect effect would be the complexing of a cation by FA so preventing its precipitation. At this time the direct involvement of humic substances in physiological reactions under field conditions requires further investigation.

4.1. Recommended levels of SOM in soils

As has been discussed earlier in this report, amounts of SOM in soils continue to decrease under current agricultural practices. New and lower equilibrium levels are being established continually. For these reasons it is not possible at this time to predict the ideal level of SOM for any soil or farming system. In Great Britain, where the SOM in some soils has reached equilibrium levels, estimates were made in the late 1960's of the impact of modern farming methods on soil fertility and structure. It was concluded (Newbould, 1982) that SOM was an important determinant of soil fertility and a key influence on structure in unstable soils. The latter were thought to contain large amounts of fine sand, very fine sand or silt and a SOM content below 3%. Thus, a minimum SOM level of 3% was considered essential for a productive sandy soil. The only minimum SOM value for Canadian soils which the author could find in the literature, is that ascribed by de Kimpe (1986) to Côté (1980). The latter suggested a value of 5%. While precise minimum SOM levels are not available at this time, levels of SOM can be maintained or even slowly increased by the uses of grasses and legumes, return of straw with added fertilizer, and applications of farm yard manure.

4.2 Future research needs

During the writing of this report a number of research needs became apparent. The most important of these are:

1. Characterization and identification of the unknown organic forms of N, P and S, which contain large portions of these elements in plant available forms;

2. Characterization and identification of organic binding agents active in the formation of soil aggregates;

3. Development of methods for the quantitative determinations of the biomass and "active" or "labile" SOM.

4. Collection of information on the dynamics of SOM decomposition, with special emphasis on the turnover rate of the biomass.

5. Determinations of minimum SOM levels required for maintaining good soil structure and high crop production.

6. Evaluation of the effect of zero tillage on the biodynamics of SOM.

5. Summary

1. SOM exerts physical, chemical and biological effects on soil quality by serving as a soil conditioner, nutrient source and substrate for microbial activity.

2. SOM contributes to the maintainance of an adequate and stable soil structure by acting as binding agent in the formation of aggregates thus ensuring satisfactory drainage and aeration and providing protection against erosion, enhancing mechanical soil properties and playing a major role in water retention.

3. SOM acts as a source and storehouse of N, P and S and of micronutrients essential for plant growth. It complexes with many metals and makes them available to plants and microbes and buffers soils against drastic changes in pH. SOM also interacts with pesticides and assists in their degradation and detoxification.

4. SOM serves as a substrate for macro- and micro- organisms in the soil. Soil microorganisms play a major role in the formation and decomposition of SOM. It is also capable of exerting direct physiological effects on plant growth.

5. All of the effects listed above impact on soil quality and point to a vital role of SOM in soil fertility.

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SOME COMMENTS ON LOSS OR ACCUMULATION OF SOIL ORGANIC MATTER AND THEIR EFFECTS ON SOIL QUALITY.

S.P. MATHUR

The following is mainly a summary of tentative conclusions and recommendations arrived at by a review of selected literature, a perusal of Dr. Schnitzer's report on Soil Organic Matter and Soil Quality, personal observations and interviews.

Loss of Soil Organic Matter:

As farming was mechanized, farm animals and ley cropping were eliminated from many farms, and with them, disappeared two means of manuring soils to maintain or restore soil organic matter. But it was felt that the concomitant increase in fertilizer use would increase phytomass production and thus the amount of fresh organic matter added to soils as crop residues, where significant amounts of the residues are added to soils. Crop residues are minimal when silage corn or root crops are grown while the quality of cereal straws is such that unless heavily fertilized with NPK or extra fertilizer N is added, the decomposition is so slow as to cause problems of N starvation and toxicity to crops. Consequently where the profit margins are low and climate a severe constraint, the straw is often burnt in the fields, as in Canadian Prairies. In addition to its other detrimental effects, the burning of crop residues also eliminated their beneficial effects on water infiltration.

Earlier studies suggested that even though manuring, compared to complete NPK fertilization, sometimes maintained higher organic matter levels, the yields were not significantly different. The same conclusion did not remain valid in the longer term particularly when crop varieties of higher yield potentials, and capable of using greater N fertilization effectively, were introduced.

It was expected that organic matter contents in soils under modern farming systems in temperate climate would tend towards new equilibrium levels determined by the system, climate and soil type. For a particular system and site, equilibrium levels are found to decrease in the following order: NPK and FYM or crop residues alone; NPK alone; no N but PK fertilizers or FYM or crop residues; and fallow.

The tacit assumption that a new level is reached and maintained was not supported by some longer term evidence. For example, data (table 1) from Sweden indicated that cultivation continues to decrease SOM levels even in soils which have been cropped for many decades. (Newbould, 1982).

Table 1

Changes With Time in the Total Organic Matter Content (% Organic C) of Soils in Sweden

Date First Cultivated	Date of Measurement 1935	1970
Never	3.67	3.88
1600	1.91	1.81
1855	2.60	2.33
1880	3.32	2.56
1910	2.72	2.50

In the prairies of the USA and Canada where cereals were grown without rotation from about 1900 to 1935 without added fertilizers and no return of residues, where moisture - conserving Fallow/Cereal rotations were started in 1937 to check wind erosion of dry soil, the levels of SOM decreased by about 50%, 1.7% to 0.9% C. About 1.58% of the soil N in the 0 to 14 cm layer is 'lost' yearly, with lesser amounts from deeper horizons. As a result, yields are beginning to decline.

The picture is more clear where sandy soils are used for row crops, such as potatoes in eastern Canada. The decrease in soil organic matter levels is serious enough to cause losses in yield, increased need for irrigation, which in turn worsens losses of nutrients and thus reduces profit margins.

Restoration of Soil Organic Matter

The green manuring now practised in some sandy soils used for growing potatoes in Canada is apparently not sufficient for maintaining or restoring levels of soil organic matter adequately. It is therefore difficult not to agree with the European workers who state that although organic matter levels can be increased slowly by use of leys, incorporation of crop residues with added fertilizer, and heavy use of farmyard manure, there is no justification for advising farmers to change to practices that would reduce their profit margins. However, recent developments offer some hope.

Janssen (1984) has assessed the relative effectiveness of different types of organic matter for increment of humus in soil, summarized in Table 2.

Table 2

Organic Matter Remaining in Soil After Various Soil Amendments

Amendment Type	Years Since Application 0	1	3	4	8	Initial Apparent Age (Years)
	(%)					
Green manure	100	20	7	4.5	3	0.99
Straw	100	38	18	14.0	10	1.41
Litter	100	57	34	23.0	14	2.28
Farm manure	100	60	33	25.0	19	2.45
Sawdust	100	75	54	40.0	27	3.69
Peat A	100	85	71	61.0	51	5.47
Peat B	100	96	90.5	86.5	82	13.62

Whereas a slightly decomposed manure may have an initial apparent age of 2.5 years and decomposes quite rapidly, a 'biostable' composted manure may have an apparent age of 3.5 or 4 years. This table suggests that the best organic soil amendments would be peat, wood wastes or composed manures which, onced added to the soil, are not mineralized too rapidly.

Canada is rich in peat, wood wastes, as well as faces problems of disposing fisheries wastes, and animal manures which are largely moved about and stored as slurries.

Recent studies by LRRC scientists (e.g. Mathur et al 1987, 1988,) and their collaborators indicate that peat can be used as a medium for composting many materials such as fisheries wastes and liquid manures. An important feature of this work is that inclusion of peat and a set of ventillation pipes makes it possible to prepare high quality composts in less than 2 months without the use of expensive turning, mixing or energized aeration mechanisms.

As estimation just completed in collaboration with the Centre de Recherche en Sylvichimie indicates that additions of 5 to 10 tons of peat-based composts may be economic even as source of fertilizer elements alone on soils producing crops valued at $2,000 per ha or more (e.g. potatoes and vegetables). It may thus be possible to, at least on some soils, restore or increase soil organic matter levels without decreasing the farmers profit margins.

Tentative Recommendation

In addition to the objectives suggested by Dr. Schnitzer, I recommend that we consider further research on the use of peat as a partial or total medium for composting of liquid manures, fisheries, slaughterhouse and forestry wastes as a means of improving soil and environmental quality, giving an impetus to the Canadian peat industry, and creating another industry based on composting. As this may not be promising enough for areas where crop values are less than a certain amount, other means may be evaluated for improving soil quality e.g. by soil conservation and better residue management practices. We should also consider studying the effect of application of peat composts on various soil properties, soil structure, and on their ability to detoxify heavy metals, allow cometabolism of recalcitrant pesticide residues, and correct minor element imbalances.

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A PROPOSED MINERAL SOIL QUALITY CLASSIFICATION SYSTEM FOR ARABLE LAND

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INTRODUCTION

In the past several decades, the pursuit of high production and improved crop yields has increasingly led farmers to drain wetlands and sloughs, clear forests on steep slopes, improve marginal land, apply heavy doses of chemicals, use heavy machinery and practice mono-culture. This has resulted in a general acceleration of soil degradation in Canada (Coote, 1980). The cost has been high. The Standing Senate Committee on Agriculture, Fisheries and Forestry (Sparrow 1984) reported that "soil degradation", was already costing Canadian farmers more than $1 billion per year in farm income. This $1 billion per year loss, of course, is in addition to the damage to the environment such as pollution of rivers, lakes and ground water due to soil erosion and heavy application of chemicals. This $1 billion loss also did not include the ecological damages such as the loss of breeding grounds for wildlife by draining of wetlands and sloughs.

Soils on steep slopes, of poor fertility, with shallow rooting-zone, etc. are poorly suited to sustain a profitable crop yield because the capital outlay for these soils is too high in sustaining a good yield. The ability to sustain a good yield year after year with a reasonable outlay of capital is, therefore, an important criterion of a high quality soil.

The price of various grains in the world market has fluctuated wildly during the last few years and it will most likely continue to do so in the future. The flexibility of the land that allows farmers to grow alternative and more profitable crops may therefore be a major factor in determining the successfulness of a farming operation.

CRITERIA

A soil quality classification for arable land, therefore, should be based not only on "productivity" of the land but include the "sustainability" of its use from the viewpoints of both economics and environmental quality as well as the "flexibility" of the land for producing many different crops.

The use of criteria such as soil flexibility, productivity and sustainability for rating soil capability (or quality) for agriculture is not new. For example, although not specifically mentioned, climatic factors and factors related to soil productivity and sustainability are used in the Canadian Land Inventory (CLI) in classifying soil capability for agriculture (ARDA 1965). However, the climatic factors are not uniformly applied nationally and all factors (or criteria) used in CLI classification are not quantitativity defined. In a recent technical report "Land capability classification for arable agriculture in Alberta" (Pettapiece 1987), three subclasses are used to determine land capability classes. The three subclasses are: climate, soil and landscape. Criteria of the subclasses are all quantitatively defined. Each one of the subclasses is to be determined independently and the land capability class is based on a combination of the three subclasses.

If "flexibility" is defined as the number of crops a soil is suited to produce, the most important factor which determines flexibility is climate. Landscape (including slope) is one of the most important factors determining "sustainability" as it influences erosion. In addition to climate and landscape, "soil productivity" is influenced by several chemical and physical soil properties. Therefore, the basis for using flexibility, sustainability and soil productivity as criteria for soil quality for arable culture is similar to the basis for using climate, landscape and soil to characterize "land capability" (Pettapiece 1987). Although the classification system of Pettapiece was designed for the province of Alberta, it may be applicable nationally.

Following is a proposed soil quality classification system consisting of three components rated independently. A combination of the three ratings determines the soil quality class. An alternative method to rate flexibility and productivity jointly is also suggested for consideration.

Component 1 - Sustainability

The rationale for the following proposal is that soils that have a high risk of erosion (wind or water) or compaction may not be able to sustain intensive cultivation over the long-term without suffering serious loss of productivity. It is recognized that soil compaction can be reversed at a cost, but not the effects of erosion. Thus erosion is weighted more heavily than compaction in the proposed system. Soil salinity is included only to the extent that a soil landscape unit that already has some salinity may suffer more if current condition persist. As with soil compaction, salinity is often reversible at a cost, and is thus weighted less heavily than erosion. Soil acidification risk is not included since this problem is readily corrected by the use of lime. Although it is recognized that in some regions there is little limestone available at the present time, this has not been considered a sufficient reason to indicate that the use of a soil subject to acidification is not sustainable. The criteria for soil sustainability and examples of sutainability classes are tabulated as follows.

Criteria:

	Condition	Sub-Index
1. Rainfall/snow-melt erosivity (E)	0-33	1
Wischmeier & Smith (1978)	34-66	2
	67-100	3
	>100	4
2. Slope (S)	level	1
	0-3%	2
	4-9%	4
	10-15%	8
	15-30%	16
3. Landform (L)	level	1
Acton (1978)	inclined	2
	undulating	2

			Sub-Index
		rolling	3
		ridged	3
		dissected	4
		hummocky	4
		knoll & kettle	4
		steep	5
4.	Wind erosion 'C' factor (C) (Combines wind, ppt., and temp.) Lyles (1983)	0-19	1
		20-39	2
		40-59	3
		60-79	4
		>70	5
5.	Texture (G) (As related to wind and water eroison and compaction)	loams	1
		CL,SL	2
		SC,LS,SiC,VFSL,SiL	3
		Si,S,C	4
6.	Depth (R)	>1m	1
		<50cm to compact layer	2
		50-100cm to rock and cemented layer	3
		<50cm to rock and cemented layer	6
7.	Climate/drainage (Y) (related mainly to compaction risk) Chapman and Brown (1966) ID = Impefrectly drained PD = Poorly drained	no restrictions	1
		moisture zone K,L	2
		ID,PD in moisture G,H	2
		moisture zone M	3
		ID,PD in moisture K,L	3
		Chinook belt	3
		ID,PD in moisture M	4
8.	Salinity (Z) (existing)	none/negligible	1
		surf. 0.1-1% of area	2
		subsurface 5-15%	2
		surface 1-5%	3
		subsurface >15%	3
		surface 5-15%	4
		surface >15%	5

Examples: Data used in Table 1 are obtained from unpublished 1:1M soil degradation map file (Coote) and soil landscape map file (Shields).

Table 1. Determining sustainability classes for a few soil polygons across Canada.

Prov.	Poly. No.	R+Rs E	Slope S	Landf. L	Wind C	Text. G	Depth R	Clim. Y	Salin. Z	Total	Class
Nfld	92	3	16	3	1	2	1	3	1	30	4
NS	213	3	2	2	1	2	1	2	1	14	1
PEI	13	3	8	3	1	3	1	2	1	22	3
NB	48	3	8	3	1	2	2	2	1	22	3
	266	3	2	2	1	3	1	3	1	16	2
QUE	40	3	1	1	1	2	1	3	1	13	1
	751	2	8	2	1	4	1	3	1	22	3
ONT	215	3	8	4	1	2	1	1	1	21	3
	14	3	2	2	1	2	1	2	1	14	1
MAN	107	2	2	4	1	1	1	1	2	14	1
SASK	51	1	4	4	3	2	1	1	3	19	2
ALTA	644	1	2	2	3	4	1	3	3	19	2
	694	2	2	2	1	1	1	2	1	12	1
BC	41	4	4	3	1	3	1	1	1	18	2

The possible range of values for the total of the sustainability sub-indices is from 8 to 41. Considering the locations of the sample of 14 polygons above, the following tentative class definitions has been made:

Table 2. Class limits of sustainability

Total sustainability sub-index value	Sustainability class	
<15	1	High
15-19	2	Moderate
20-25	3	Low
26+	4	Unsustainable

Soils with the following properties are considered to be unsuitable: a) slope > 30%; b) bedrock or cemented layers are within 20 cm of the soil surface.

When a great number of polygons have been evaluated, and after consultations with pedologists across the country, it is likely that modifications will be made to improve both the sustainability sub-index values and the sustainability classes.

Component 2 - Flexibility

The criteria suggested (Table 3) are similar to the climatic subclass of the Land Capability Classification System proposed by Pettapiece (1987). The moisture factor (A) is, however, rated according to soil moisture regime subclasses as defined in The Canadian System of Soil Classification (Agriculture Expert Committee on Soil Survey 1987) in terms of the amount of soil moisture deficiency or surplus. Only limited soil moisture data are available for most areas of Canada. The soil moisture subclass can be estimated by a simplified moisture balance system calculated from the monthly precipitation and potential evapotranspiration in a growing season (Baier and Robertson 1965). The temperature factor (H) is rated according to effective growing degree-days. The effective growing degree-days is thought to be a better criterion than growing degree-days because it also takes into consideration the longer day-light in northern Canada during the summer months (Pettapiece 1987). The class limits of factors A and H (Table 3) are abitrary. Testing is needed to adjust them to appropriate limits.

Table 3. Criteria used to estimate Soil Flexibility Class* for Arable Land.

Moisture Limiting Factor (A)		Temperature Limiting Factor (H)	
Soil moisture regime subclass	Rating of A	Effective growing degree-days	Rating of H
Perhumid and Humid	1	> 3300	1
Subhumid	2	3300 - 2801	2
Subaquic	3	2800 - 2301	3
Semiarid	4	2300 - 2001	4
Aquic	5	2000 - 1701	5
Subarid	6	1700 - 1501	6
Peraquic	7	1500 - 1301	7
Arid	8	1300 - 1100	8
Aqueous regime	Unsuitable	< 1100	Unsuitable

*Moisture (A) and Temperature (H) are to be rated separately, the lower of the two ratings is used as the soil flexibility class.

Component 3 - Soil Productivity

Criteria used to estimate soil productivity for arable culture are tabulated in Table 4. For each criterion a sub-index similar to the one used for sustainability rating will be set up at a later date so that the rating of these criteria can be quantified. We are also planning on testing these criteria in a similar manner as the example given in Table 1 to determine the proper class limits for component 3. According to our experiences and the discussions with various soil surveyors, all soil subgroups of the Canadian System of Soil Classification are classified in relation to soil productivity (Table 5). The soil productivity class is commonly higher than the CLI soil capability class due to the fact that climatic factors are usually not considered in the soil productivity classification. Table 5 is useful in using available information in a soil landscape file for determining soil quality class.

Table 4. Criteria used to estimate Soil Productivity Class for Arable Land.

Surface Soil Factors 0 - 20 cm	Subsoil Factors 20 - 120 cm
Texture (M)	Texture (m)
Structure and consistence (D)	Structure and consistence (d)
Organic carbon content (F)	--
Soil reaction (V)	Soil reaction (v)
Carbonate content (K)	Carbonate content (k)
Salinity (N)	Salinity (n)
Surface stoniness (P)	--
	Rooting depth (r)
	Drainage (w)

Table 5. Classifying Soil Subgroups to Soil Productivity Classes for Arable Culture.

Class 1	Class 2		Class 3		Class 4	Unsuitable	Notes
O.MB	GL.MB	PZ.GL	GL.EB	GL.R	DU.DYB	O.TC	1. Drop one class if the control section has a texture of sand; loamy-skeletal or clayey-skeletal.
E.MB	GL.EMB	GL.GL	GLE.EB	GLCU.R	GLFR.GL	BR.TC	
O.BL	O.EB	GLD.GL	DU.SB	B.SO	P.HP	R.TC	
R.BL	E.EB	GLBR.GL	GL.SB	DB.SO	DU.HP	GL.TC	
CA.BL	O.SB	SZ.GL	GLE.SB	BL.SO	FR.HP	O.SC	
E.BL	E.SB	O.FHP	O.DYB	DG.SO	P.FHP	BR.SC	2. Drop two classes if particle-size is sandy-skeletal.
O.DG	O.DB	LU.FHP	E.DYB	G.SO	DU.FHP	R.SC	
R.DG	R.DB	SM.FHP	GL.DYB	GLB.SO	FR.FHP	GL.SC	
CA.DG	CA.DB	O.HFP	GLE.DYB	GLDB.SO	P.HFP	FR.LG	3. Following soils are rated as unsuitable:
O.GBL	E.DB	LU.HFP	O.B	GLG.SO	DU.HFP	OT.HP	
BR.GBL	GL.DB	SM.HFP	R.B		FR.HFP	OT.FHP	- Fragmental particle-size;
O.GL	SZ.DB	O.R	CA.B		B.SZ	GLOT.FHP	- pH (in 0.01M $CaCl_2$) of surface soil $\leq$ 3.0;
D.GL	GLE.DB	CU.R	GL.B		DB.SZ	OT.HFP	- > 50% carbonates in surface soil;
BR.GL	GLR.DB	GL.HR	SZ.B		BL.SZ	GLOT.HFP	- E.C. > 12 ds/m in surface soil;
O.HR	GLCA.DB	GLCU.HR	GLR.B		A.SZ		- Aqueous moisture regime;
CU.HR	GLSZ.DB		GLCA.B		GLB.SZ		- Gleysols on depressions;
	GL.BL		GLE.B		GLDB.SZ		- Surface stoniness classes 4 and 5.
	GLE.BL		GLSZ.B		GLBL.SZ		
	SZ.BL		FE.HG		B.SS		
	GLR.BL		O.G		DB.SS		
	GLCA.BL		R.G		BL.SS		
	GLSZ.BL		FE.G		DG.SS		
	GL.DG		O.LG		G.SS		
	SZ.DG		FE.LG		GLB.SS		
	GLR.DG		GLPZ.GBL		GLDB.SS		
	GLCA.DG		FR.GL		GLBL.SS		
	GLSZ.DG		GLPZ.GL		GLG.SS		
	O.HG		GLSZ.GL				
	R.HG		O.HP				
	HU.LG		GL.FHP				
	PZ.GBL		GLSM.FHP				
	GL.GBL		GL.HFP				
	GLBR.GBL		GLSM.HFP				

DETERMINING SOIL QUALITY CLASS AND SUBCLASSES

a) Soil quality class

The soil quality class is determined by soil-quality-index which is the sum of the classes of the three components (i.e. flexibility, sustainability and soil productivity). If any one of the three components is rated as "unsuitable", the soil quality class is automatically to be rated as "unsuitable". Other than unsuitable classes, there are four classes in each of the sustainability and productivity components and there are eight classes in the flexibility component. Therefore the range of soil-quality-index is from 3 to 16. The relationship between soil-quality-index and soil quality classes is as follows:

Soil-quality-index	Soil quality class
3 to 5	1 V. high
6 to 8	2 high
9 to 11	3 medium
12 to 14	4 low
15 to 16	5 marginal

b) Soil quality subclasses

Soil quality subclasses are used to indicate the limiting factor or factors in each soil quality class. Up to three criteria listed in Tables 1, 3 and 4 can be used as suffix of a soil quality class to form subclasses. There should be no subclass for class 1 soils as there is no significant limiting factor in these soils. A soil quality rating of 3CA, for example, means the class 3 soil has problems with wind eroison and soil moisture.

An Alternate Method for Evaluating Flexibility and Soil Productivity Jointly.

Dumanski et al. (1988) used the following equation to calculate Physical Land Flexibility Index (PLF) for the prairie region of Canada.

$$PLF = \sum_{i=1}^{n} Si\ Yi/Ymi$$

where Si = portion of soil map unit variously suited for crop i (%);
Yi = anticipated fresh weight potential yield (kg ha^{-1}) for crop i;
Ymi = maximum anticipated fresh weight yield (potential yield) for crop i in the study area (kg ha^{-1});
n = number of crops used in the analyses

PLF indices were calculated for the prairie region based on 8 crops (spring wheat, corn, soybean, phaseolus bean, barley, oats, canola and sunflower). After comparison of PLF with land flexibility estimated through evaluation of soil and climate suitability Dumanski et al. (1988) concluded that the PLF is the superior. The yield (or production) factor is incorporated in the PLF in addition to the soil and climate factors. The weights of soil and climate factors attributed to soil flexibility are best balanced by the yield factor.

CONCLUSION

Potentially, PLF may be the best criterion to evaluate soil flexibility nationally. At this moment, PLF is available only for the prairie region. The determination of PLF indices for all cultivated soils in Canada should be of high priority for soil quality or land evaluation projects. If PLF is found to be suitable for evaluating soil flexibility, the third component of soil quality (i.e. soil productivity) may no longer be needed because both the climate and productivity components are incorporated in the PLF.

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